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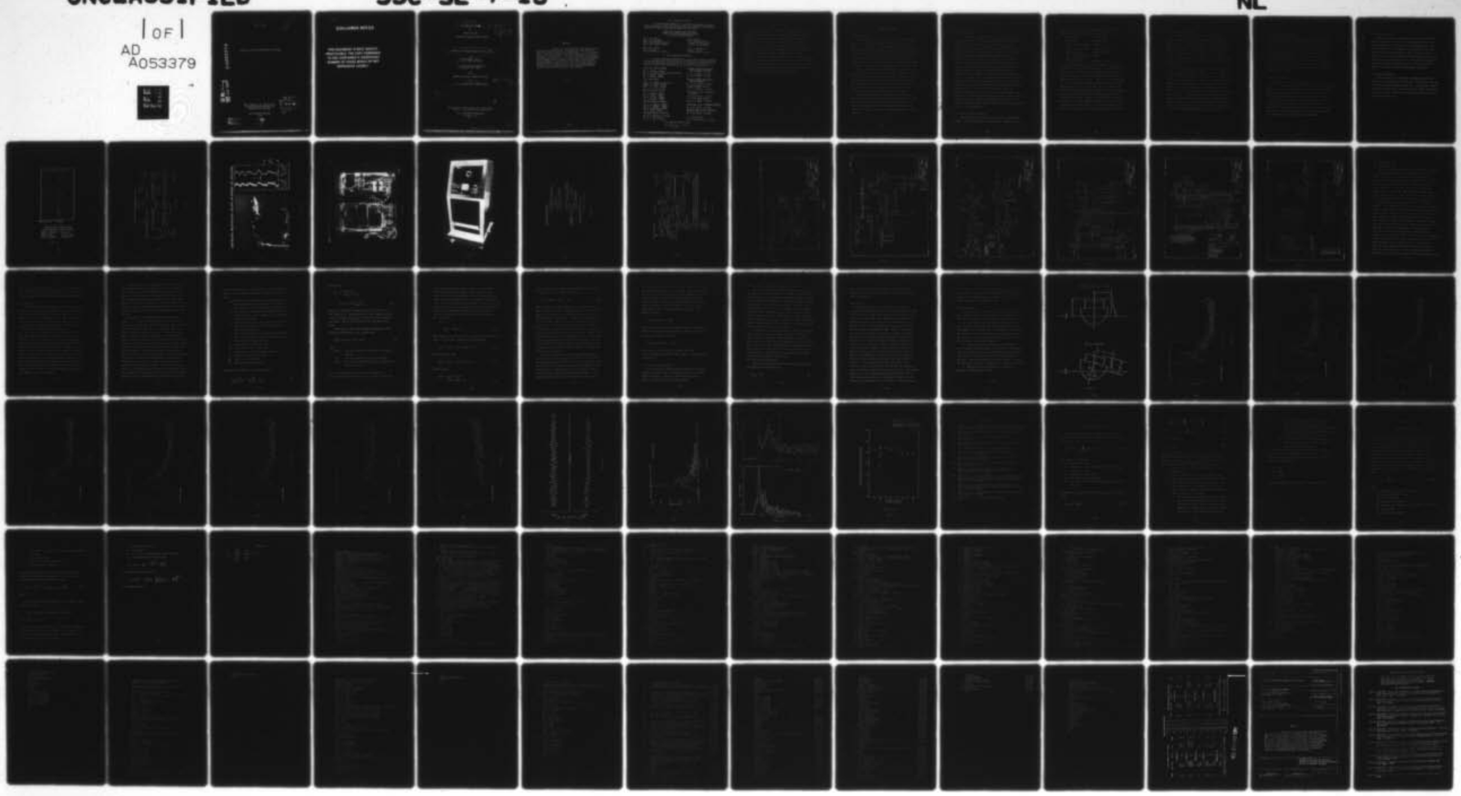

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9 FINAL TECHNICAL REPORT, 11 Apr 78

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12 80p

Project SR-1234

"Shipboard Waveheight Radar System"

6 A REPORT ON SHIPBOARD WAVEHEIGHT RADAR SYSTEM.

by

10 D./Chen ~~and~~ D./Hammond

U.S. Naval Research Laboratory
Washington, D.C. 20375

under

NAVSEA Work Request N00024-75-WR-51625

and

U.S. Coast Guard 15 MIPR-Z-70099-4-43693

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ABSTRACT

A microwave shipboard wave-height radar sensor for measuring ocean wave spectra, developed by the Naval Research Laboratory, was installed on the containership *S.S. McLEAN*, February, 1975. The sensor's performance, design, and analysis of data for one data run are discussed. The radar system has a 3 centimeters wavelength, 2 nanoseconds pulse width, 100 watts of peak transmitted power, 10,000 pulse per second repetition rate, 2-foot parabola antenna diameter, 7 decibel receiver noise figure, 100 pulses per second equivalent pulse processing rate, and a 1-foot resolution. Results are in reasonable agreement with airborne measurements. Areas for improving the system are also discussed.

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Acknowledgments

The authors of this report wish to thank Kalen J. Craig for his indomitable spirit in developing the radar system and also the testing and evaluating it at sea. The assistance of James Kenney in preparing the equipment for use in the 1974-1975 season is greatly appreciated. Mr. Charles Buhler's skill in the assembly of the antenna package was an excellent example of assistance from the support services at NRL. Mr. E. A. Uliana's programming assistance made the data analysis possible. The cooperation from the personnel from the Teledyne-Ryan Corporation and the crew of the S.S. McLean made our task much easier. Without the help from any of these individuals, success in this effort may not have been possible.

SHIPBOARD RADAR

1.0 Introduction

The ability to measure the wave spectra in the open ocean from a moving vessel has met with varying degrees of success. Each sensor to date has suffered in its performance due to environmental conditions or due to its placement for measuring the unperturbed sea. This report will discuss the utilization of a microwave sensor on a moving vessel for measuring the open ocean wave spectra. Employing microwaves, some of the limitations of other sensors are not experienced.

Tucker [1] developed the Tuckermeter for measuring the wave spectra from a moving ship by sensing changes in water pressure due to surface wave conditions. The Tuckermeter is placed below the water line and thus requires calibration for each wave frequency, ship speed, and depth. Since the sensor operates on pressure, it performs as a low pass filter and will not sense the higher frequencies.

A microwave shipboard wave height radar sensor for measuring the ocean wave spectra was developed by the Naval Research Laboratory (NRL) and was installed on the S.S. McLean in February 1975 and its performance, design, and analysis of data for one data run will be discussed in this report.

2.0 Radar System

2.1 Introduction

Any sensor that profiles the ocean surface and measure the height variations can provide the necessary information for deriving the wave spectra. Since radar is a range measuring device, it lends itself ideally for this purpose. Profiling waves with a radar requires that the radar employ a very narrow antenna beam and very narrow pulses. The narrow antenna beam illuminates a small spot size on the ocean surface and the narrow transmitted pulse width permits resolving the fine height structure of the waves. Using a radar with these features on a tower, the radar returns clearly show the ability of the system to profile the ocean as shown in Figure 2-1. In addition the narrow antenna beam permits the radar to be aimed away from the nadir allowing measurements of the ocean unperturbed by the bow wake of the moving vessel. Microwaves also permit the radar to be operated day or night, in rain or fog, with bow spray or no bow spray, and continuously or intermittently. However, the radar is ineffective when a solid sheet of water splashes across the antenna beam. This situation occurs so infrequently that it can be discounted.

2.2 Radar System Parameters

The radar's high resolution of one foot is achieved by using a very narrow pulse of 2 nanoseconds. Figure 2-2 is a

functional block diagram of the radar system; and the principal characteristics of the radar system are:

Wavelength	3 centimeters
Pulse Width	2 nanoseconds
Peak Transmitted Power	100 watts
Pulse Repetition Rate	10,000 per second
Antenna Diameter	2-foot parabola
Receiver Noise Figure	7 db
Equivalent Pulse Processing Rate	100 per second

The R.F. components for the transmitter and receiver are mounted in a watertight enclosure on an antenna pedestal located about 90 feet above the ship's water line. The antenna is pointed abeam and tilted down and out about 15 degrees with respect to nadir. Figure 2-3 is a photograph of the antenna mounted on the starboard side of the ship's bridge and the figure to the right shows a sample of the measured data before processing. Figure 2-4 shows transmitter (upper box) and receiver (lower box) as they are mounted inside the watertight enclosure. The control and display circuits are located remotely from the transmitter-receiver assembly in a standard half rack as shown in Figure 2-5. All the timing and control signals are derived in this unit.

2.3 Principle of Operation

The 10 KHz timing generator, shown in Figure 2-2, triggers the transmitter and synchronizes the receiver signal processing. The R.F. transmissions consist of 2 ns wide pulses at 10 GHz carrier frequency with a peak power of 100 watts and with a pulse repetition rate of 10,000 per second. The reflected R.F. signals from the ocean is amplified in the receiver to a usuable level. Employing an envelope detector on the amplified signal results in a 2 ns wide video pulse.

Processing the 2 ns wide pulses requires circuitry in the system with bandwidths of 500 mHz. It is desirable to operate at a lower bandwidth where components are more easily used and obtained. By employing a sampling scope for display and signal processing, it is possible to make this bandwidth transformation which is equivalent to a video pulse that is 200 *microseconds* wide or a bandwidth of 5 KHz. Thus the use of standard low speed logic circuits can be used for signal processing resulting in a simpler and more reliable system. The principle of operation of a sampling scope is well known and will not be discussed. See references [2, 3, 4] for the particular scope used in this radar.

2.3.1 Automatic Gain Control

The block diagram for the automatic gain control (AGC) is shown in Figure 2-6. The amplitudes of the returned pulse is changed due to (1) scattering from a rough surface, and/or (2) large changes in the viewing angle. The effect of the scattering is to induce rapid changes in pulse amplitude while the changes due to viewing angle are much slower and are on the order of tens of seconds. The time constants in the AGC loop are adjusted to compensate for the slow changes of ship's roll but will not affect the rapid pulse-to-pulse changes.

2.3.2 Range Tracker

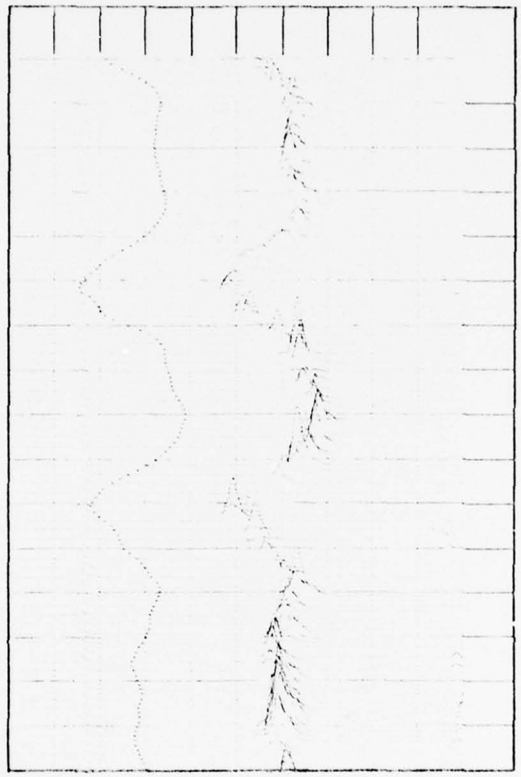
The block diagram for the range tracker is shown in Figure 2-7. The remote programming feature of the Tektronix 3T5 sweep unit [4] is used in the range tracking loop. Employing this feature permits the range tracker to automatically adjust the time delay of the scope trigger so that the returned video pulse always remains centered on the sampling scope screen. The details of the tracker are shown in Figures 2-8, 2-9, 2-10, and 2-11. The signal flow and logic controls are quite involved and will not be discussed here. This information will be provided if requested.

2.3.3 Output Signal

The range tracker follows the peaks and crests of the waves and produces an output voltage proportaional to the range excursions. The voltage to be recorded changes one volt for each 12.8 feet change in the distance of the radar antenna from the ocean surface. When as many as fifty successive range pulses have been missed, indicating loss of range lock, an error light is lit. The AGC meters shows the value of attenuation inserted in the receiver amplifier which is a measure of the returned signal amplitude.

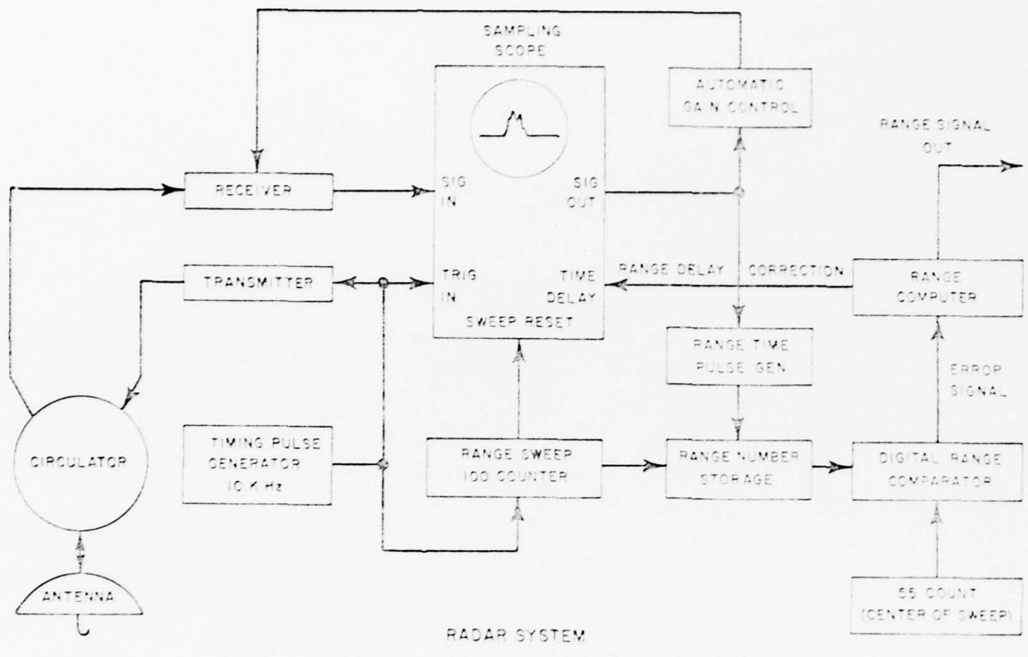
2.4 System Drawings

The drawings of the system are included so that the details of the system can be trace out. The drawings include a simplified block diagram, Figure 2-8, a total radar system schematic, Figures 2-9, 2-10, and 2-11, the cable connections and control panel, Figure 2-12, and the transmitter-receiver schematic, Figure 2-13.



PULSE DATA FROM THE
CHESAPEAKE LIGHT TOWER
WAVE HEIGHTS 5 FEET
HOR. SCALE 2.5 FT/DIV
VERT. SCALE 1 SEC/DIV

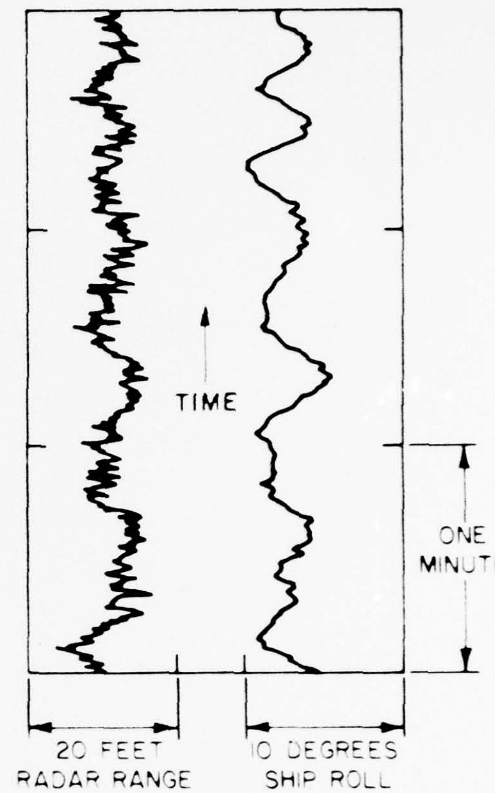
Figure 2.1



RADAR SYSTEM

Figure 2.2

SHIPBOARD WAVEHEIGHT RADAR ON-BOARD SS-McCLEAN



UNPROCESSED RECORDED DATA

Figure 2-3

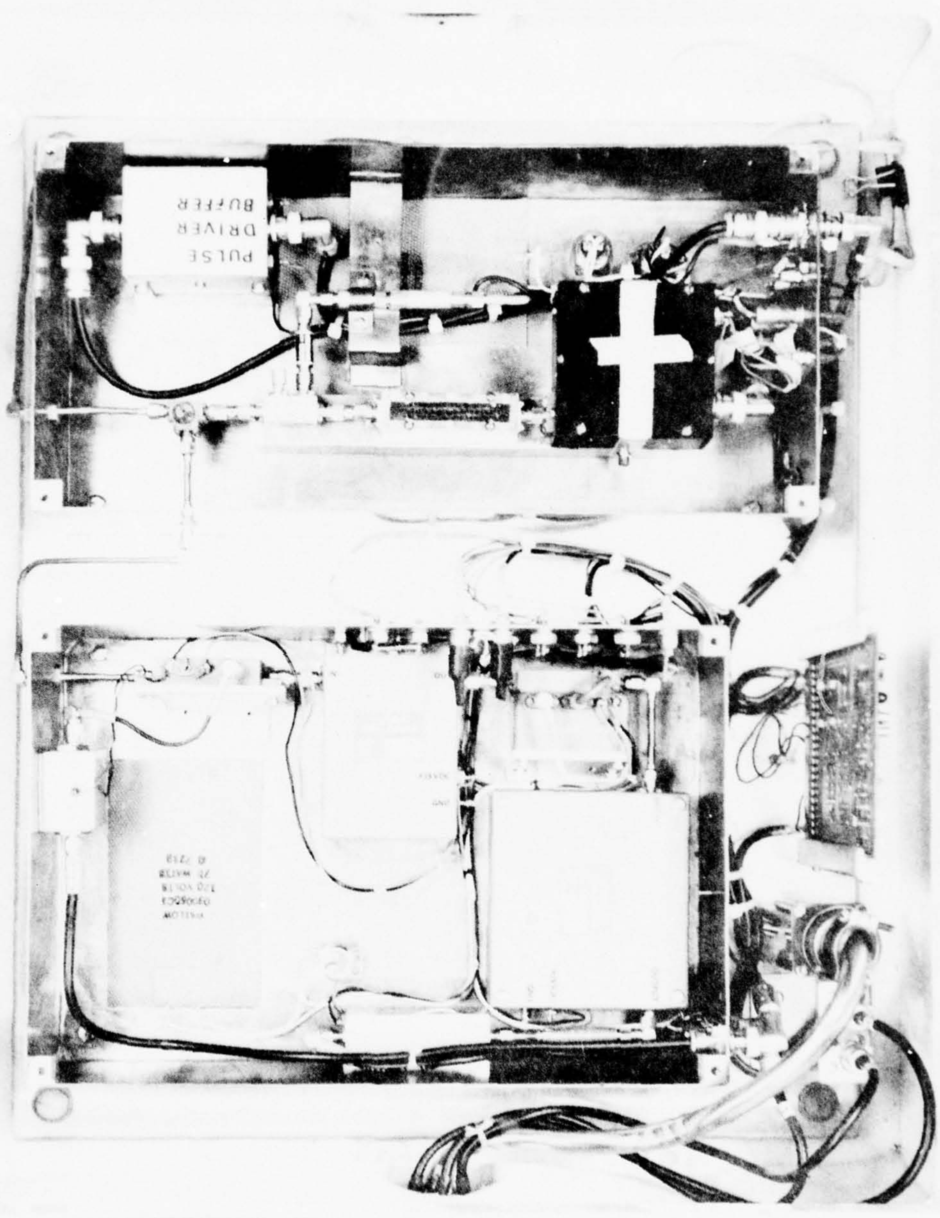


Figure 2-4

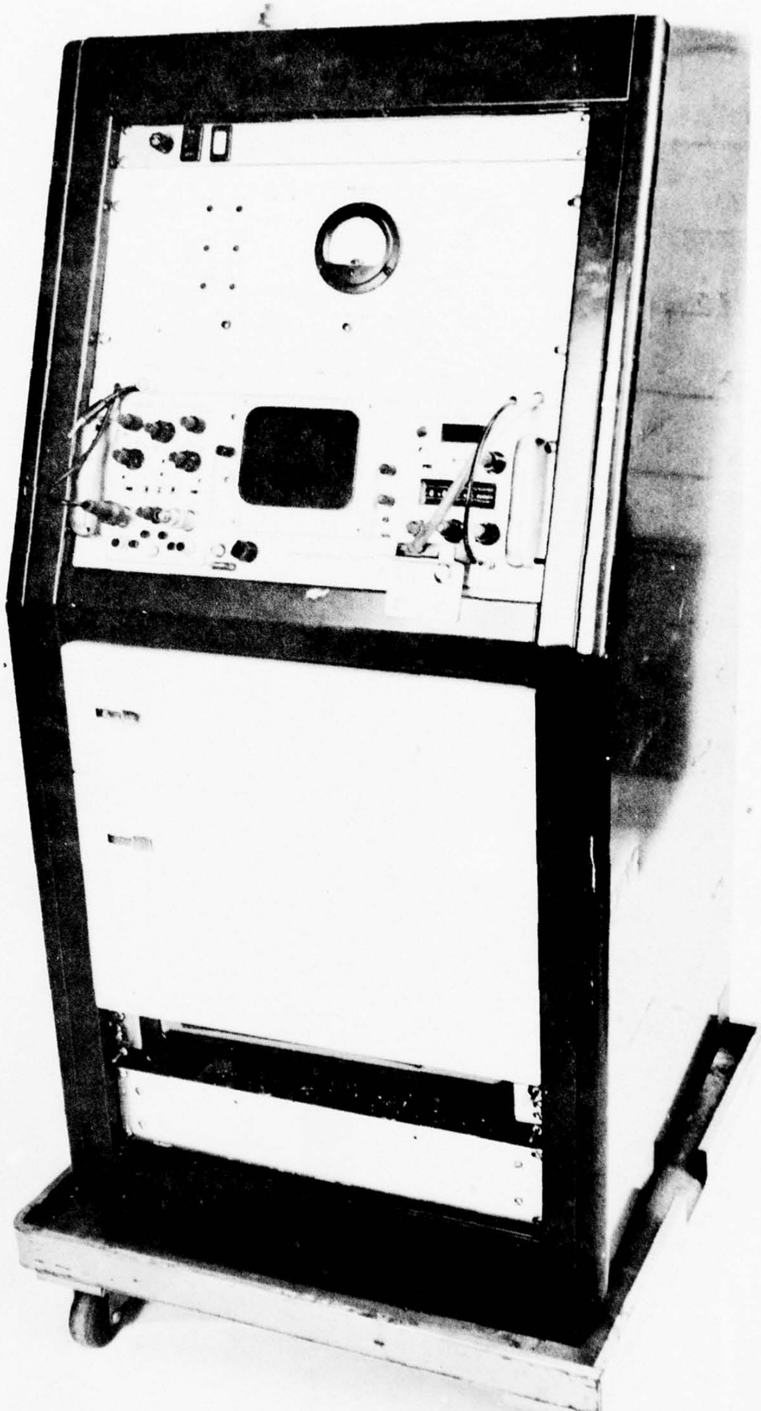
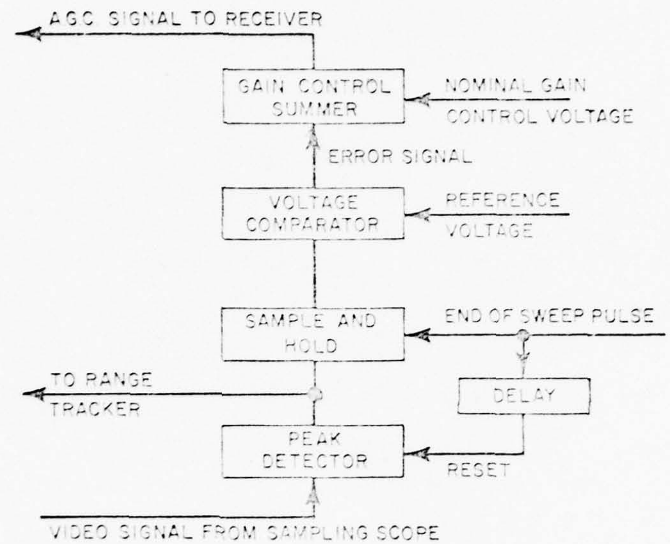
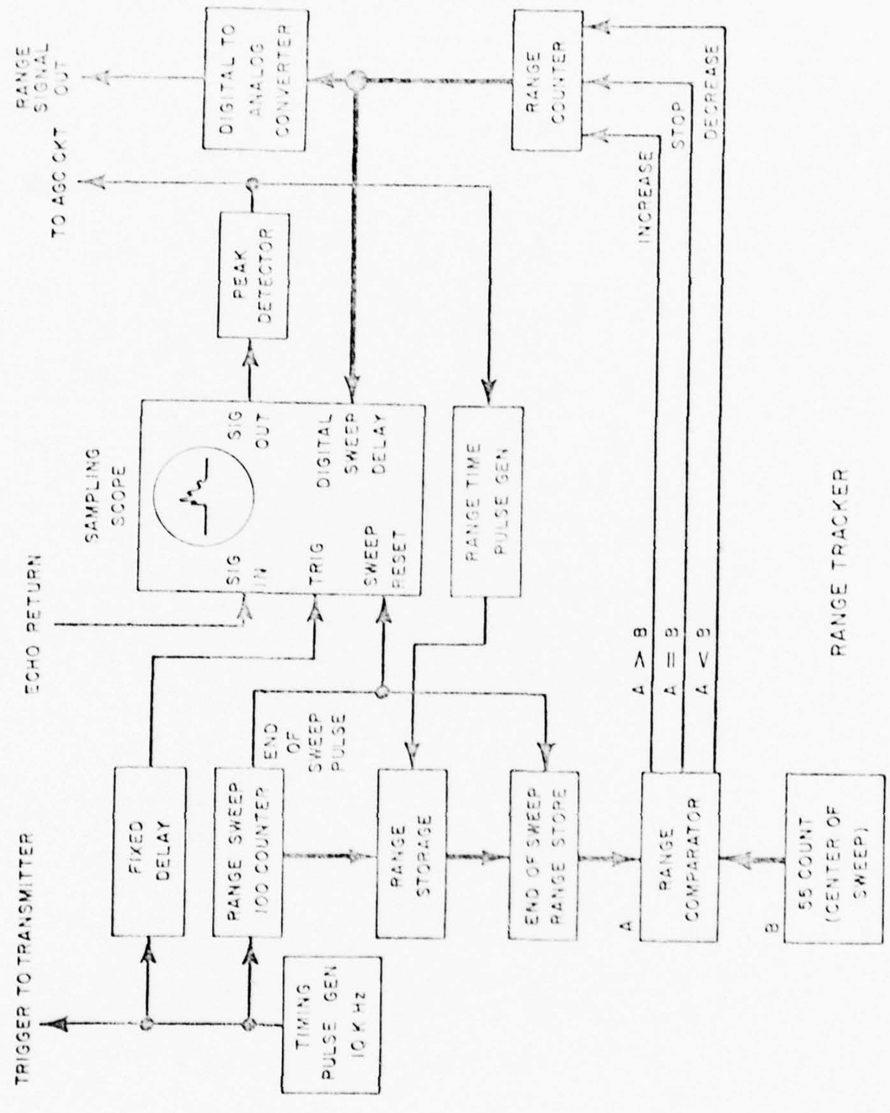


Figure 2-5



AUTOMATIC GAIN CONTROL

Figure 2.6



RANGE TRACKER

Figure 2.7

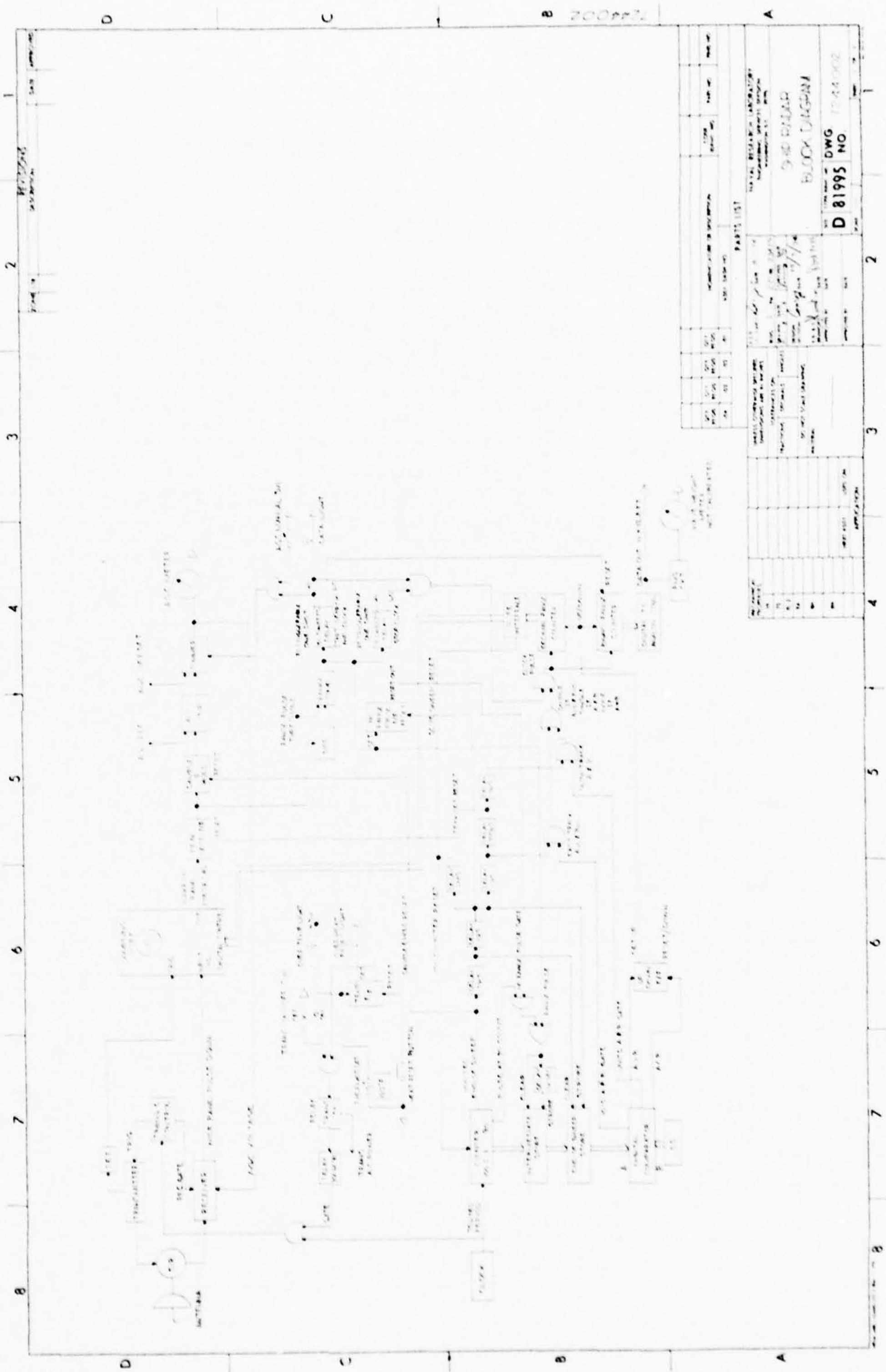


Figure 2.8

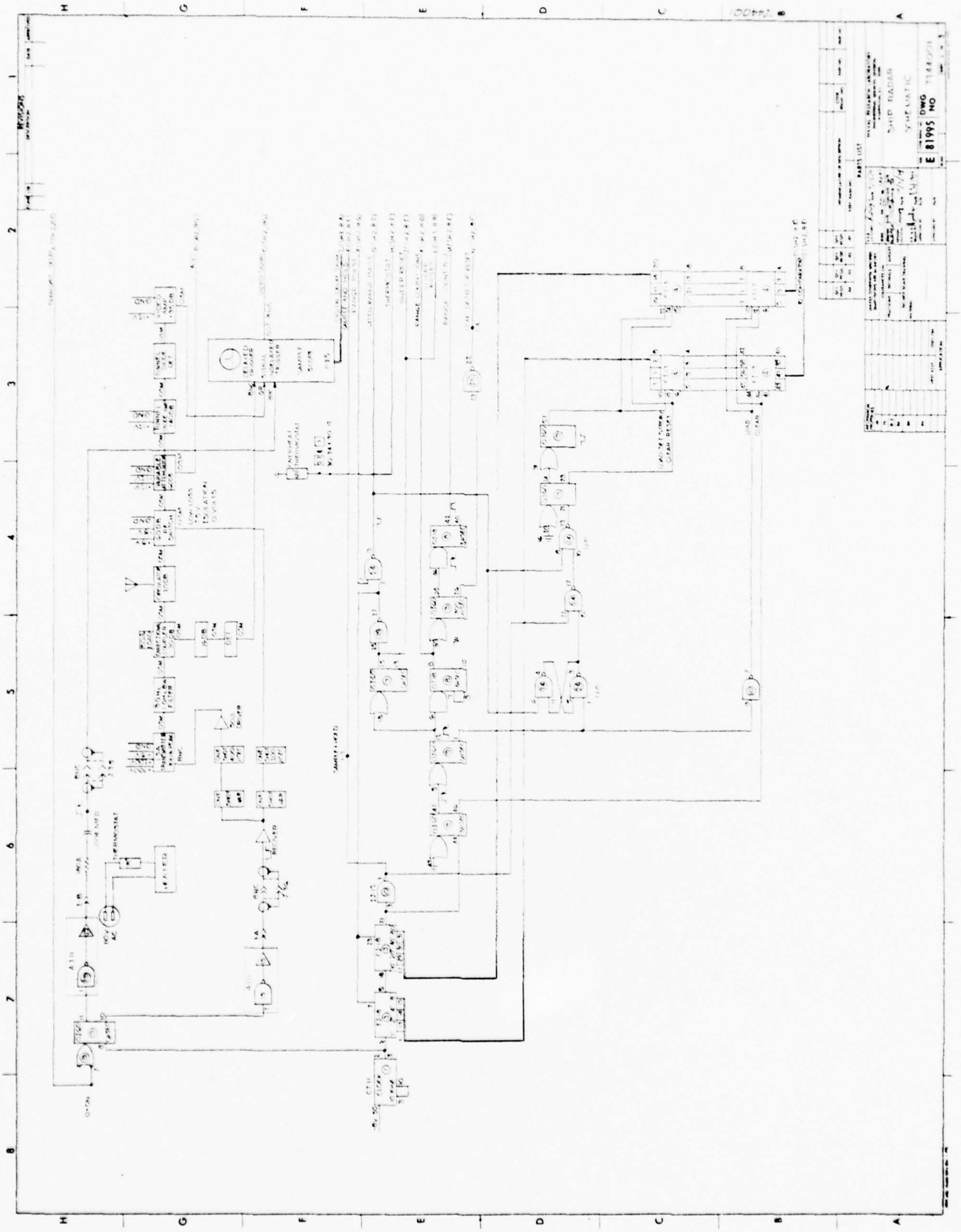


Figure 2.9

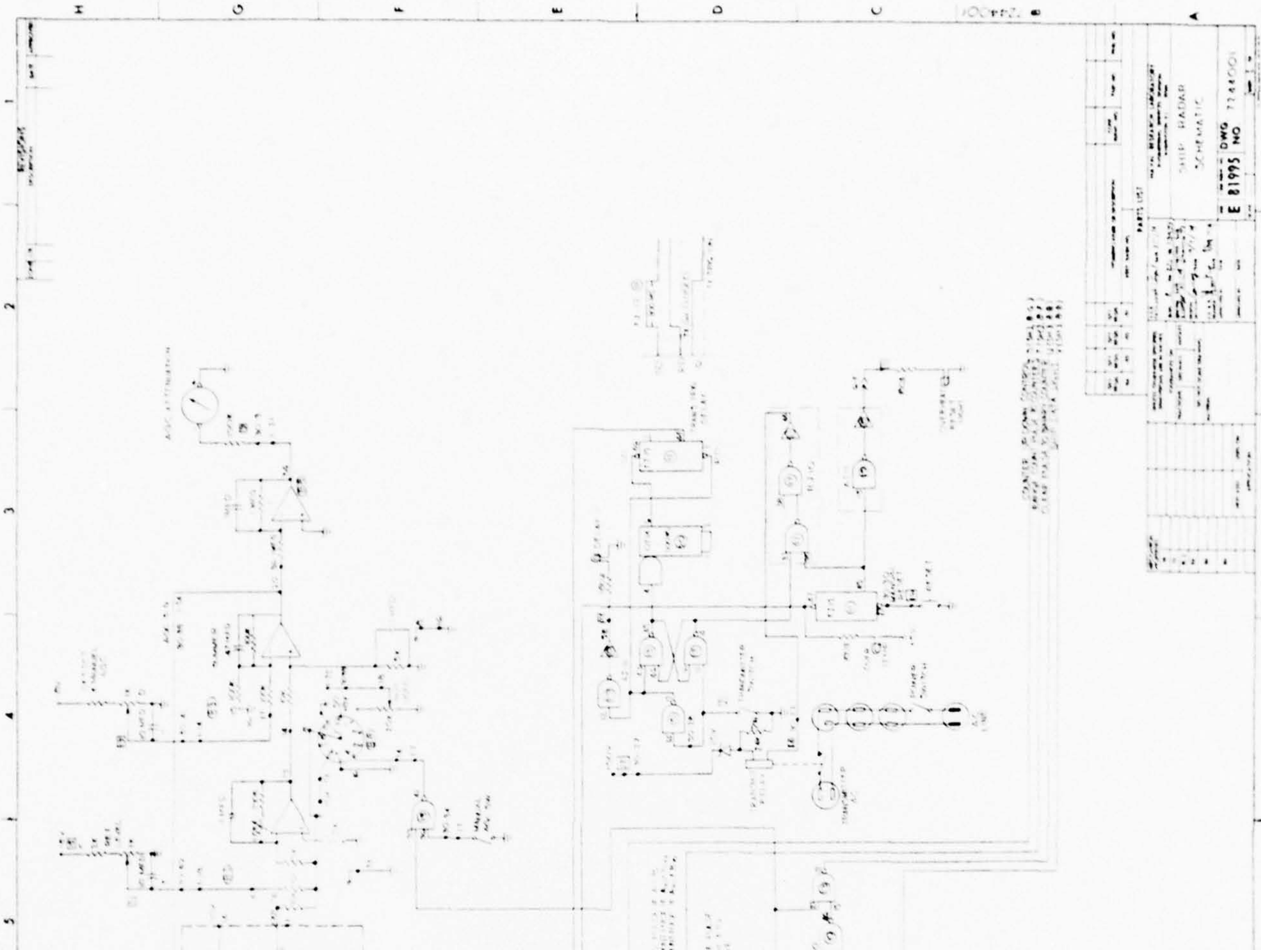


Figure 2.10

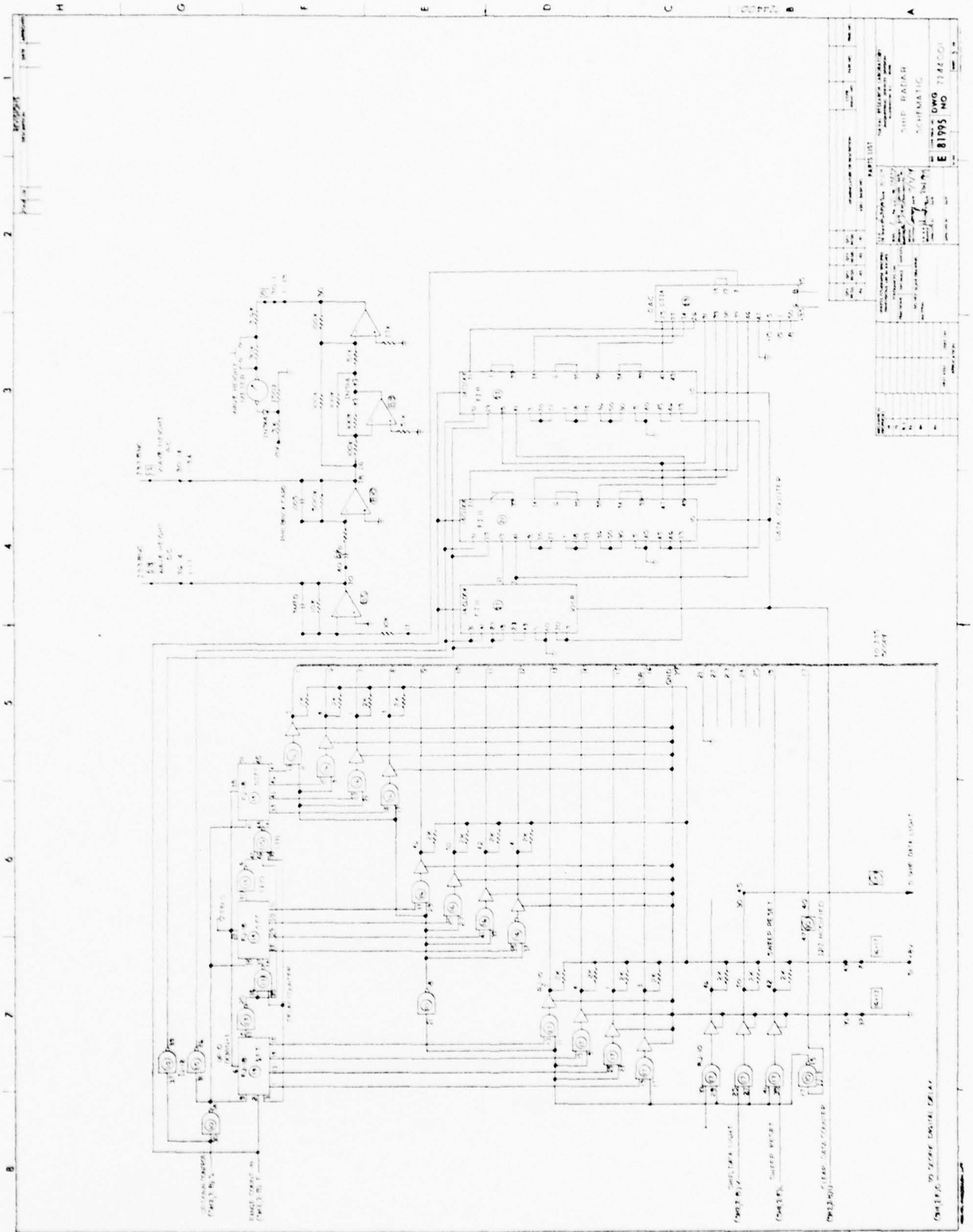


Figure 2.11

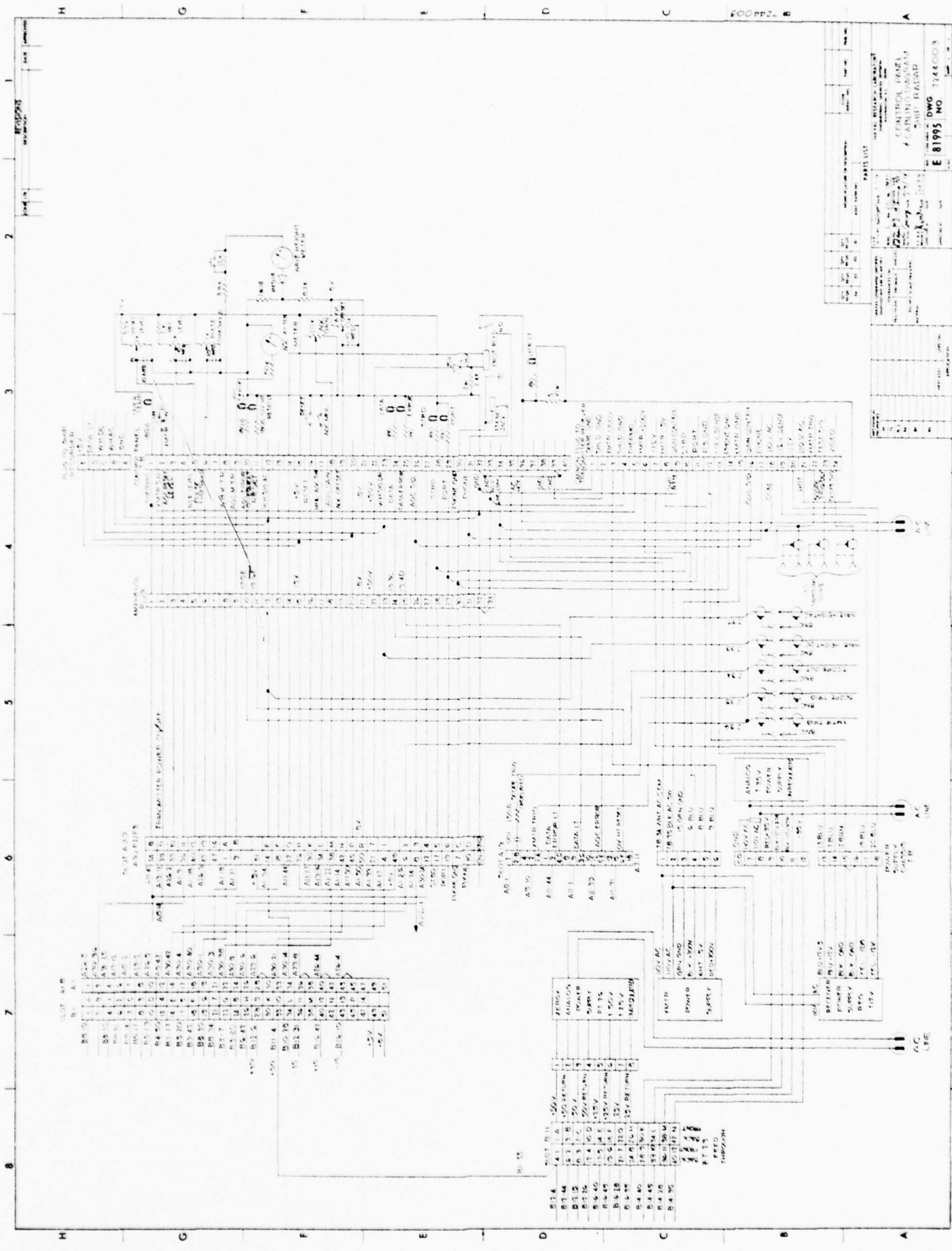


Figure 2.12

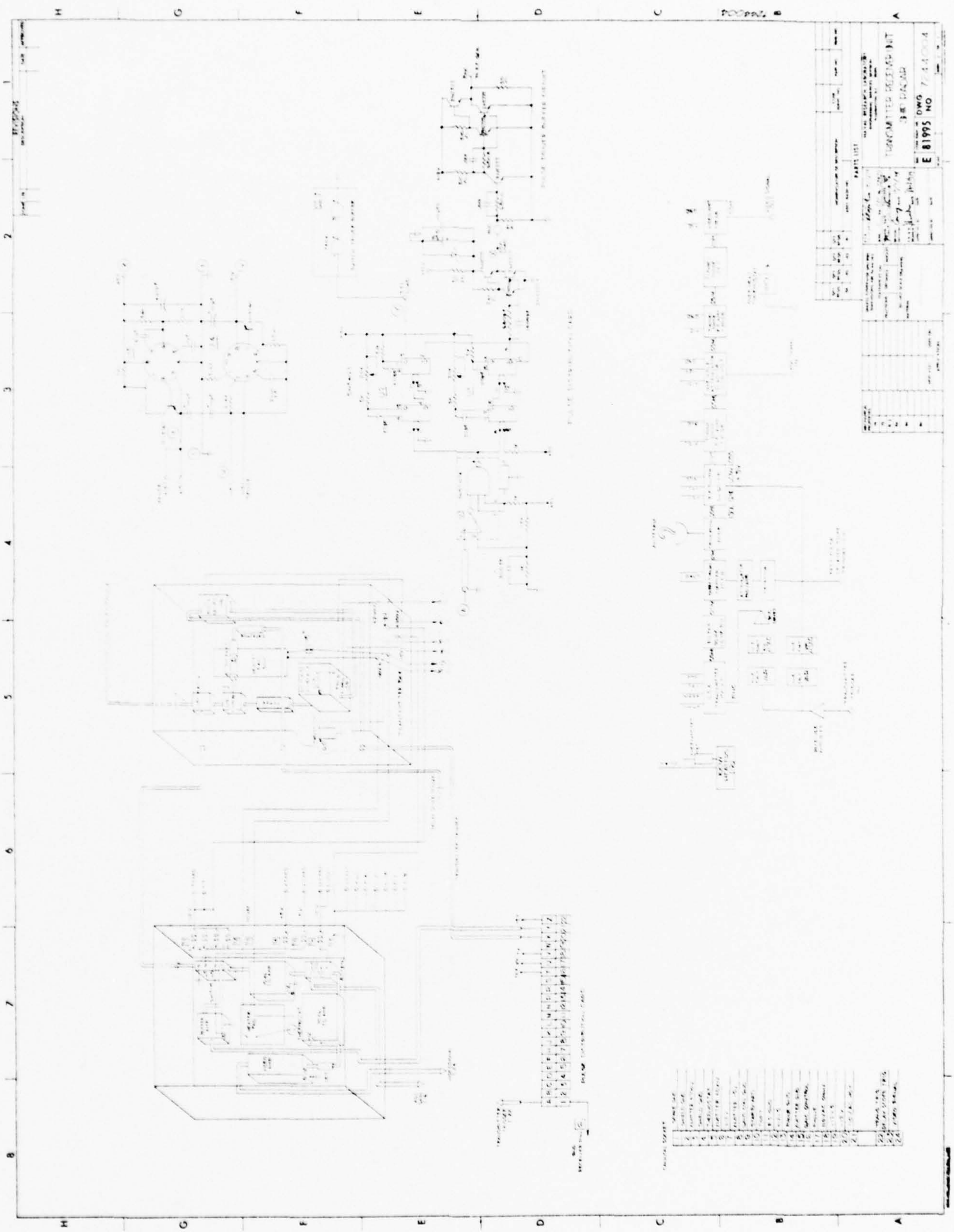


Figure 2.13

3.0 Data Reductions

3.1 Experimental Test

The nanosecond radar is located starboard on the bridge of S.S. McLean and adjusted to view the ocean at a look angle of 15° from nadir and away from the bow wake. On February 6, 1975, while the ship was underway from Elizabeth, New Jersey to Portsmouth, Virginia, simultaneous ocean surface data was taken by the shipboard radar while an airborne laser profilometer and airborne nanosecond radar were measuring the same seas. The object of this effort is to establish the validity of the shipboard measured data.

The shipboard radar data was recorded at 30 minute intervals starting at 8:20 A.M. EST on February 6, 1975 and ended at approximately 2:00 P.M. of the same day. Each file of data started with about a minute of zero level setting and followed by a minute of calibrations. The ship was travelling at 29 knots at 214° heading. Approximately 9:26 A.M. the aircraft intercepted the ship's track at 38°3' N in latitude and 74°41' W in longitude. Airborne data was recorded at 500 feet and at 1000 feet altitude in the immediate vicinity of the ship's path. At 500 feet altitude, a laser profilometer [5] and an airborne nanosecond radar were used to profile the ocean surface. At 1000 feet altitude, NRL's airborne nanosecond radar was operated in the wave spectrometer mode. Aircraft data was recorded continuously at intervals of about 90 seconds as the aircraft

was flying at 146 knots ground speed. Exact coincidence of data taking was not possible and comparison of the data is based on approximate times from the ship and aircraft logs.

3.2 Analysis

The dynamics of the two platforms (aircraft and ship) while recording ocean surface data was significantly different. In addition to their peculiar motion characteristics, the data was recorded in different manners. One, continuously in analog and the other, intermittently and digitally. To effect a better comparison of the data, it was necessary that the data be reduced to some common base.

The analog shipboard data was recorded in real time, and then sampled and digitized at 8 Hz off-line. This digitizing rate was a compromise, taking into account the longest ocean wavelengths expected to be experienced by the ship and the storage capacity of in-house computers to process the data. The aircraft data was digitized at 90 Hz rate in real time but was utilized at 15 Hz rate off-line. Again a compromise was made with the high frequencies which were not overly significant being truncated and at the same time trying to maintain equal spatial resolution with the shipboard data. The data storage and handling capacity of the computer was also of concern.

The largest amount of dynamic motion or movement other than forward velocity of a ship is its roll. In Figure 2-3 was shown a sample of the shipboard radar output and the output of the roll sensor. The magnitude and the period of the roll which affect the determination of the true ocean wave spectra must be removed before any real analysis can be conducted. However other motions also need to be corrected for unless they become second order in magnitude and can be ignored.

The geometry of the radar aboard ship is shown in Figure 3-1. The upper figure shows the direction of the ship moving into the paper and in still water thus remaining in the upright position. The radar measures R(t), the distance from the radar to the surface of the water at an angle α with respect to the vertical. As the ship moves, the radar distance, R(t), changes with the peak and crest of the waves. It is the magnitude and frequency of these radar distance variations that yields information for determining the ocean spectra. As mentioned earlier, ship motions, particularly roll, affects the magnitude of these variations yielding an erroneous wave height change. In the lower illustration of Figure 3-1 is shown an instantaneous roll position that the ship can assume. In this situation, the change in radar distance R(t) is not due to waves but is due to the ship's motion and the radar then measures the distance R_θ instead of R_o. The magnitude of the change in R_o to R_θ

needs to be determined. The geometry, assuming rigid body motion, for determining this change is shown in Figure 3.1 where

- H_o = distance from radar antenna to water surface, in the direction of ship's symmetric axis, and 0° roll angle; 76 ft. for H_o in these calculations.
- H_θ = distance from radar antenna to water surface in the direction of ship's symmetric axis, caused by θ degrees roll angle.
- L_o = horizontal distance of radar antenna from center of gravity of the ship at 0° roll angle, 40 ft. for these calculations.
- θ = angle of roll; positive in clockwise convention, from vertical upright position, by looking into the direction of ship's heading.
- R_o = radar distance of 0° roll angle,
- R_θ = radar distance at θ° roll angle,
- α = look angle of radar antenna, 15 degrees,
- CG = center of gravity of the ship,
- MC = metacenter of the ship,
- BC = buoyant center of the ship.

From the Law of Sine's, it can be shown that

$$\frac{R_\theta}{\sin(\frac{\pi}{2} - \theta)} = \frac{H_\theta}{\sin(\frac{\pi}{2} + \theta - \alpha)} . \qquad (1)$$

Rearranging

$$R_\theta = H_\theta \frac{\sin(\frac{\pi}{2} - \theta)}{\sin(\frac{\pi}{2} + \theta - \alpha)}$$

$$= (H_o - L_o \tan\theta) \frac{\cos\theta}{\cos(\theta - \alpha)} \qquad (2)$$

where R_θ is the radar distance to the water surface at a roll angle of $\theta°$. Using Equation (2) the values for $R_\theta(t)$ can be determined from H_o, L_o, α, which are given and the roll angle θ which can be obtained from the ship's roll sensor.

Using $R_\theta(t)$ in the radar distance measurements, the following relationship can be established:

$$R_R(t) = R_\theta(t) + \zeta(t) + \Delta R(t) \qquad (3)$$

where

$R_R(t)$ - the radar distance measurement to the water surface

$\zeta(t)$ - the instantaneous apparent wave height

$\Delta R(t)$ - the radar distance changes due to ship motion other than roll.

This relationship shows the effect of ship motion in conjunction with wave motion and their effect on the radar

range measurements, but assumes that any flexure which changes the distance between the radar antenna and the center of gravity is negligible. All other motion changes such as yaw, pitch and heave, etc. are combined into $\Delta R(t)$. $\zeta(t)$, the term of interest in describing the sea surface, is small in magnitude and it modulates the distance $R_R(t)$ which is large. The shipboard equipment was designed only to record this modulation and as a result a large distance bias, D, remains.

Let

$$R_A(t) = R_R(t) - D \tag{4}$$

where $R_A(t)$ is called the relative radar range measurement and D is a constant. Substituting (3) into (4),

$$R_A(t) = R_0(t) + \zeta(t) + \Delta R(t) - D \ . \tag{5}$$

Rearranging the terms

$$R_A(t) - R_0(t) = \zeta(t) + \Delta(t) - D. \tag{6}$$

Redefining (6)

$$\begin{aligned} R_1(t) &= R_A(t) - R_0(t) \\ &= \zeta(t) + \Delta R(t) - D \ , \end{aligned} \tag{7}$$

where $R_1(t)$ is the relative radar range without the effect of ship's roll. Rearranging the terms

$$\zeta(t) = R_1(t) - [\Delta R(t) - D] \quad . \tag{8}$$

This results in $\zeta(t)$ describing the sea surface variations. There still exist $\Delta R(t) - D$ which has not been accounted for because D is basically a DC term. This however can be removed by filtering the data. $\Delta R(t)$, as defined, consist of all the other ship motions affecting the radar range measurements. The high frequency components of $\Delta R(t)$ are of such low magnitude that their effect on the wave measurements is negligible, whereas the low frequency component can be effectively removed with a high pass filter. $\zeta(t)$ still contains a doppler term and it must be taken care of before it is possible to study the ocean surface characteristics. In Appendix A the filtering process employed to remove the $\Delta R(t)$ term is discussed.

The term $\zeta(t)$ describing the amplitude variations of the waves as the radar profiles the surface while the ship is underway includes a doppler term. Due to the velocity of the ship and the doppler effect, the waves encountered are foreshortened. Thus the wavelengths measured are not the true ocean wavelength but an apparent wavelenth. If the radar's instrumentation had incorporated a coherent R.F.

signal, the effect of the ship's velocity can, by appropriate instrumentaion, be subtracted directly. Since this is not the case, it is necessary to correct the apparent spectra to a true spectra. In order to accomplish this, it is no longer possible to operate in the time domain but one must resort to working in the wave number or frequency domain. Thus the time function must be transformed into a wave number function:

$$\zeta(t) \text{ transforms } \rightarrow \psi_A(k_A)$$

where k_A is the apparent wave number because of the doppler effect and $\psi_A(k_A)$ is the apparent wave number spectrum. It can be shown, Appendix B, that

$$\psi_A(k_A) \text{ transforms } \rightarrow \phi(\sigma_T)$$

where $\phi(\sigma_T)$ is the true wave frequency spectrum. $\phi(\sigma_T)$ is the spectrum shown in the results. Equation (B-2) in Appendix B.

3.3 Fast Fourier Transform

A fast fourier transform [6] was used in the spectral analysis and since this is standard operation, it will not be discussed here. However it was necessary to use a Hamming function [7] to smooth the spectra.

3.4 Spectral Bandwidth Vs. Spectral Resolution

The 2-foot parabolic antenna illuminates a footprint [8] about 3.11 feet in diameter at a radar range of 80 feet. This footprint size can only resolve wavelengths larger than six feet which is equivalent to an apparent cutoff frequency of 0.908 Hz. The true cutoff frequency is 0.358 Hz after removing the Doppler effect. Translating this true cutoff frequency into a true wave period results in wave period of not less than 2.8 seconds. The high pass filter, discussed earlier, removes wave periods in the data larger than 7 seconds. The wave spectra shown in the results are calculated for the wave period window of 2.8 to 7 seconds.

If different spectral bandwidths are desired, the upper frequency bound can be raised by increasing the antenna size. The lower frequency bound can also be extended but this requires removing the ship's motions without the use of high pass filter. The analysis requires ship motion sensors at the site of the antenna to record the actual excursions of the antenna. In this manner it is possible to resolve the longer wavelengths of the spectra.

3.5 Significant Wave Height

Significant wave heights were determined from Equation (9) employing the following [9]

$$H_{1/3} = 4\sqrt{E} \tag{9}$$

where $H_{1/3}$ is the significant height and E is the total energy of the waves, which is obtained by integrating the wave spectrum curve.

3.6 Results

Wave spectra from the shipboard measurements are presented in Figure 3-2 to 3-9. The significant wave heights for files 1 to 8 of the data, respectively, are 6.90, 7.29, 7.33, 7.11, 7.10, 6.53, 6.53, and 6.37 feet. Since the sea was not in steady state conditions and fetch-limited seas did not exist, it is not possible to make comparison with the Pierson-Moskovity spectrum [10]. Airborne mesurements are presented in Figure 3-10 and 3-11. Figure 3-10 shows the measurements made by laser profilometer and the nano-second radar. Figure 3-11 shows the analyzed results from the airborne measurments. Laser profilometer registered 6.04 feet and the nanosecond radar registered 4.70 feet as the significant wave height based on data while flying at 500 feet. At 1000 feet, operating the nanosecond radar in wave spectrometer mode yielded significant wave height of 6.60 feet. All airborne measurements were made in the vicinity of the ship during part of the time the shipboard radar was recording data that is shown in file 2. Accordingly, Figure 3-11, the airborne measurements and Figure 3-3 of the shipboard measurements are combined in Figure 3-12 for comparison. The shapes are very similiar. The significant

wave heights of all the measurements shown in Figure 3-13. The data are in reasonable agreement, expecially when time coincidence of the data is not possible and the aircraft covers such large area about the ship.

3.7 Discussions

In any system, one can always find areas for improvement, and this radar is no different. After conducting the anlaysis of the data, several points should be noted.

1. Future radars for this purpose should record the total range as well as the range modulation by the waves. The advantage is to enable one to make absolute corrections for the ship motions; otherwise, only relative corrections can approximately be made for ship motions, and still leave the DC offset as an unknown quantity.

2. A shipboard radar measurement of wave spectra permit viewing the undistrubed area of the sea. With better time and spatial resolution and by employing accelerometers on the antenna, the ship motion effects can be removed directly. Three accelerometers and three angular sensors at the site of the radar are recommended for future measurements.

3. Shipboard radars can operate in all types of weather, twenty-four hours a day.

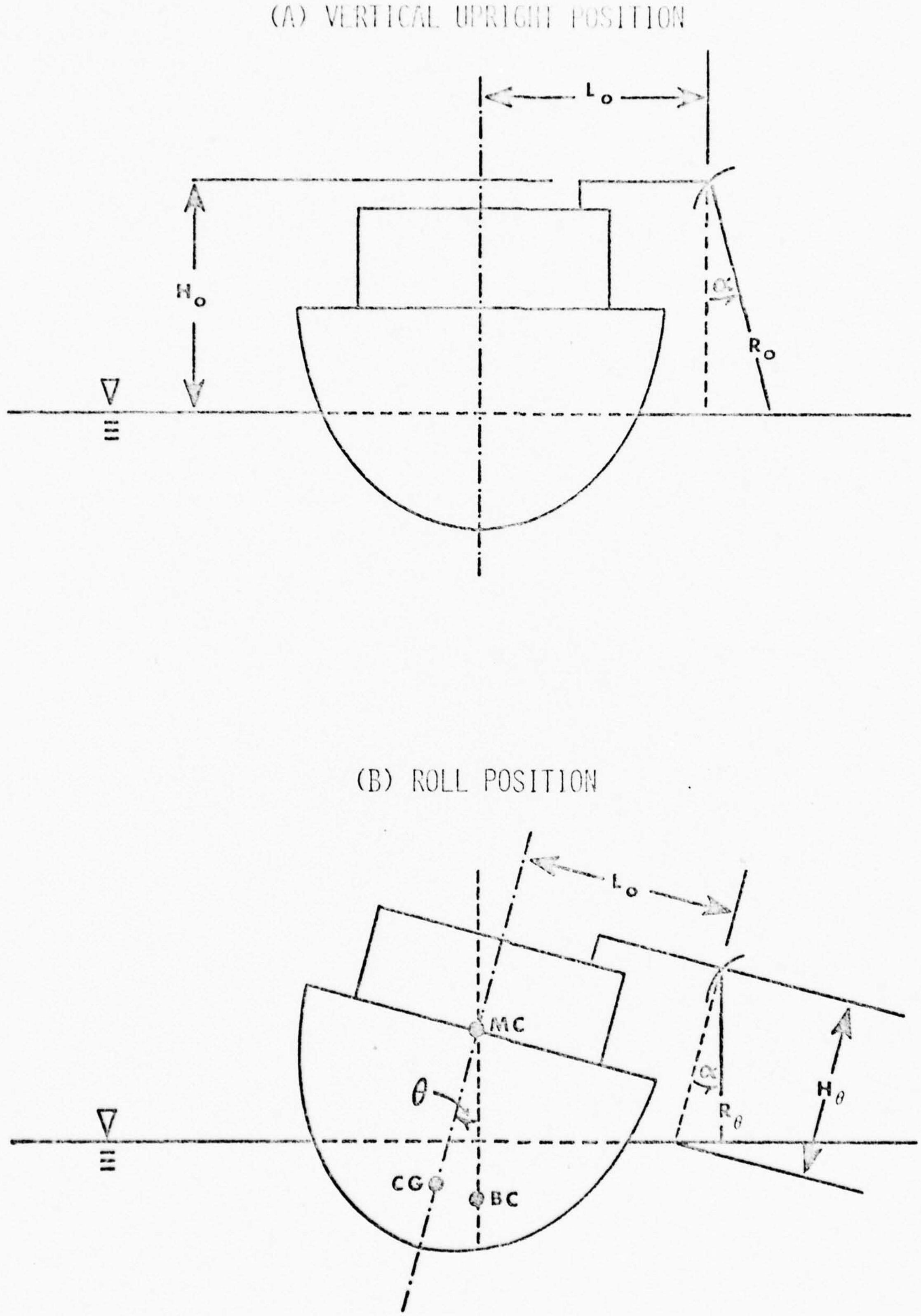

(A) VERTICAL UPRIGHT POSITION
L_o
H_o
α
R_o
(B) ROLL POSITION
L_o
MC
θ
α
R_θ
H_θ
CG
BC

Figure 3-1

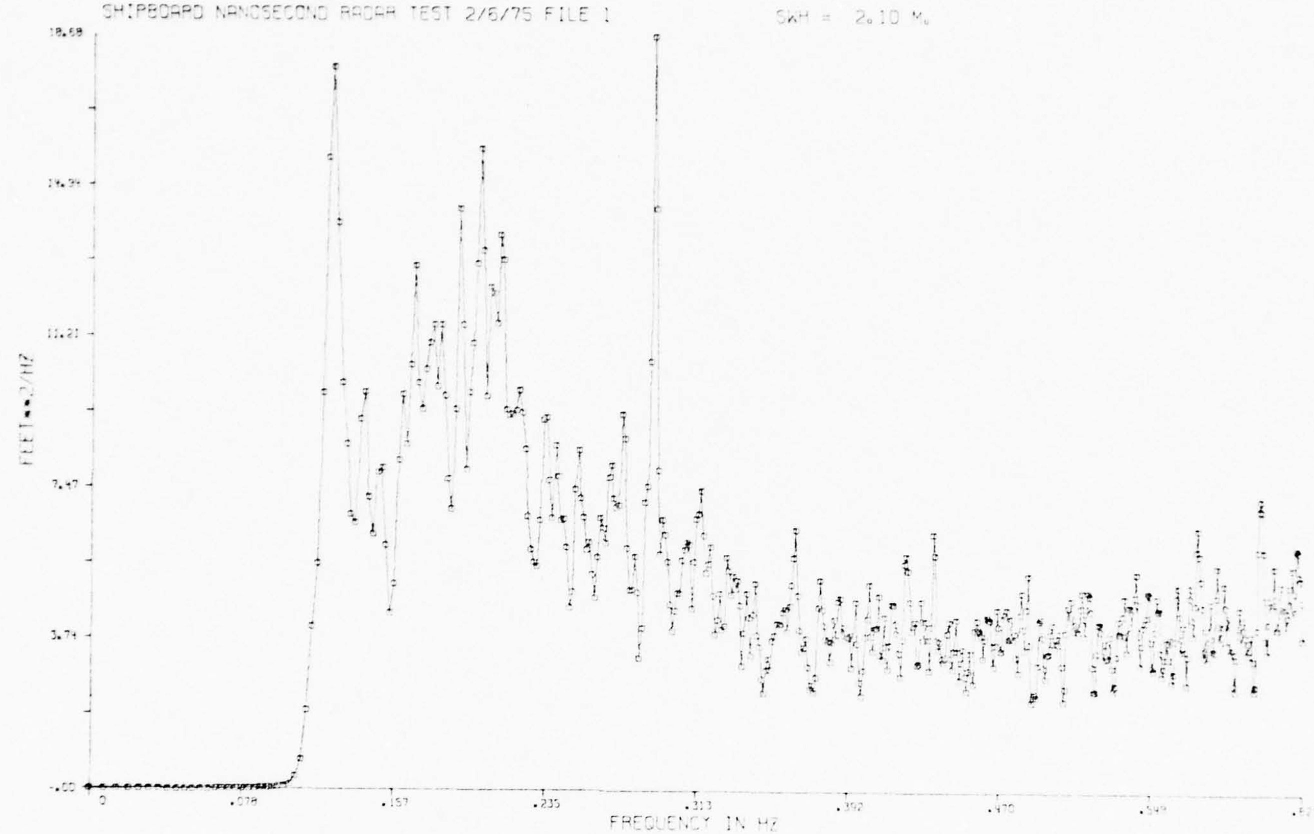

SHIPBOARD NANOSECOND RADAR TEST 2/6/75 FILE 1
SWH = 2.10 M.
FEET**2/HZ
FREQUENCY IN HZ
18.68
14.94
11.21
7.47
3.74
.00
0
.078
.157
.235
.313
.392
.470
.549
.627

Figure 3-2

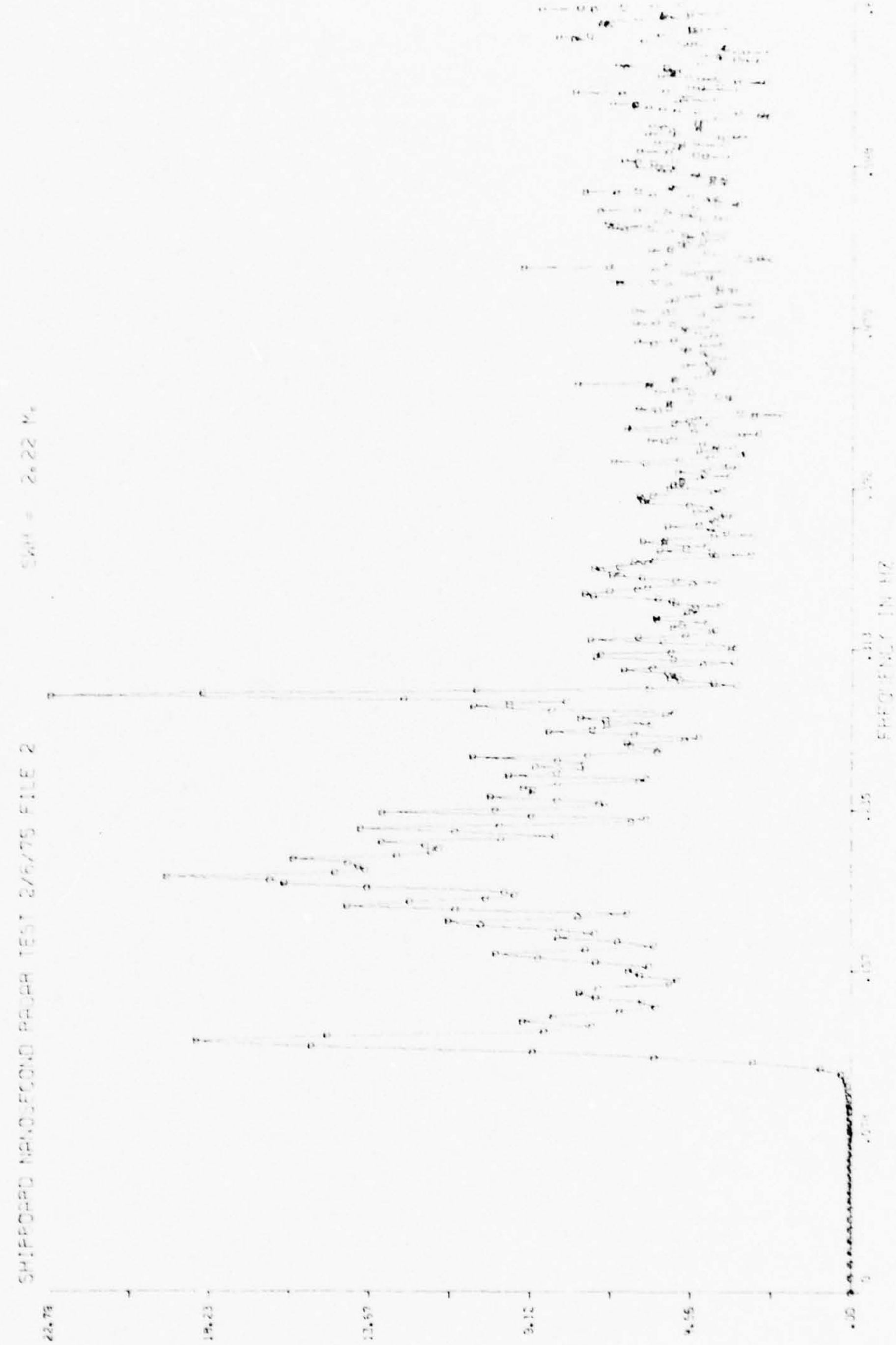


Figure 3-3

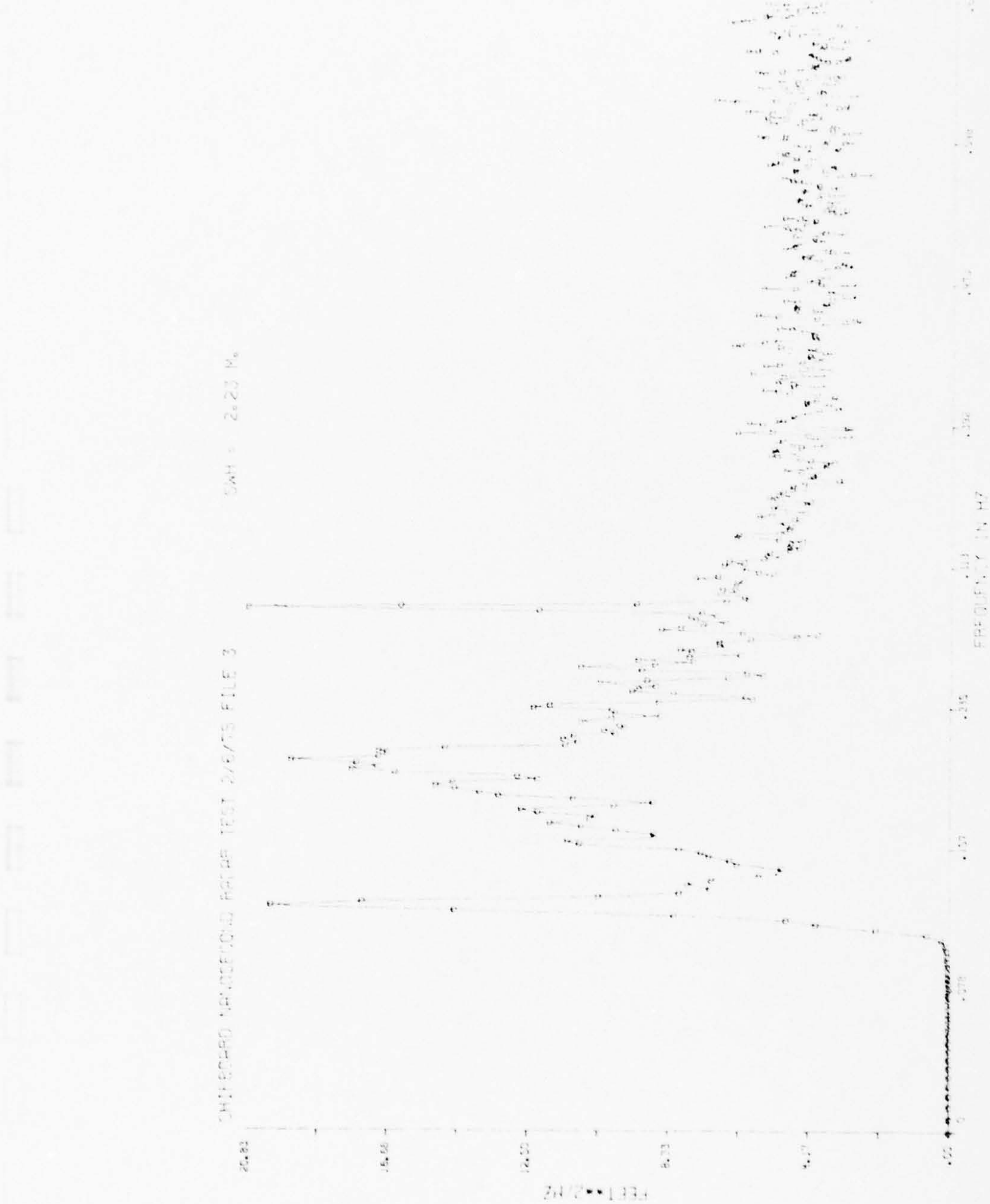


Figure 3-4

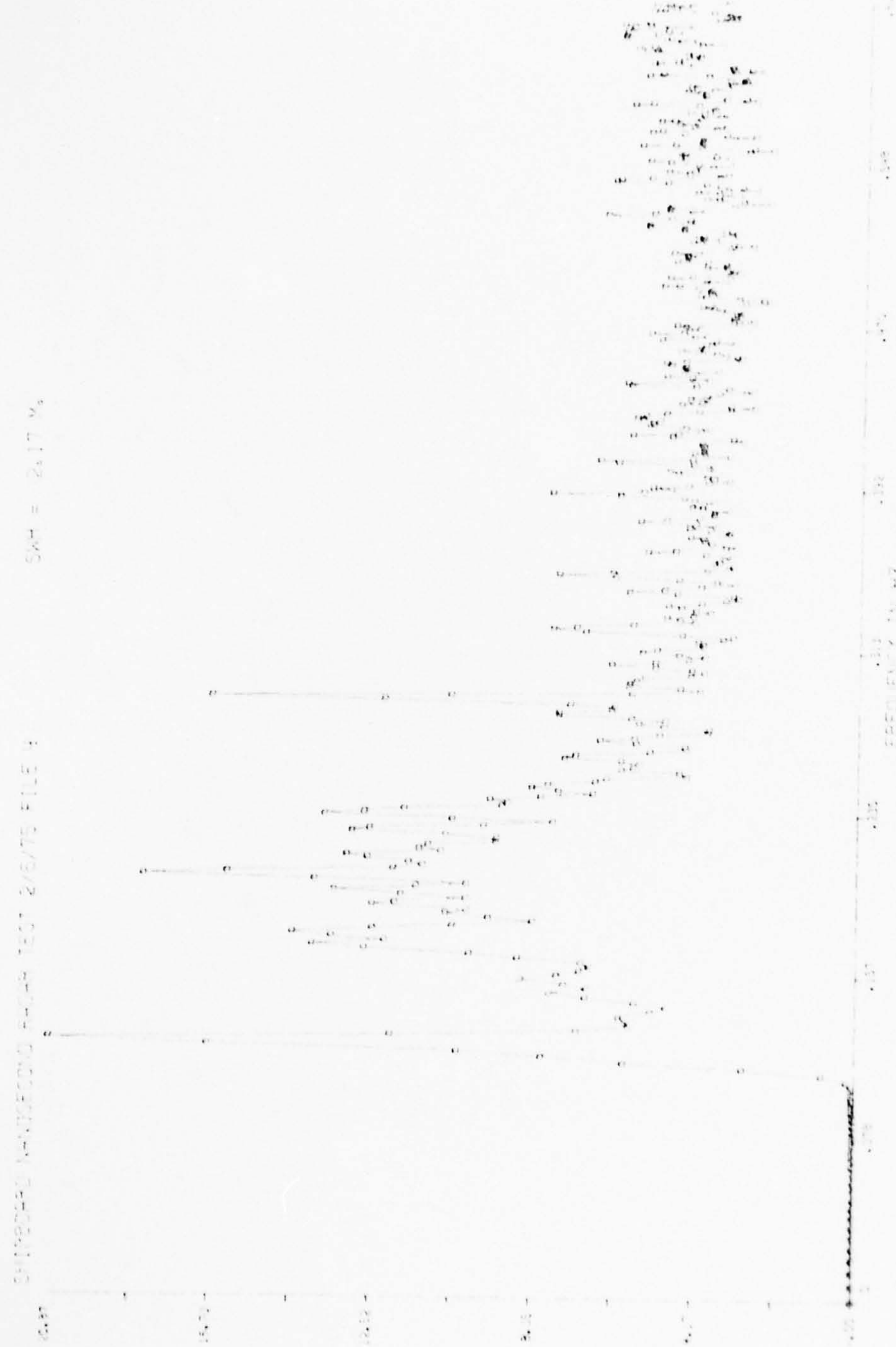


Figure 3-5

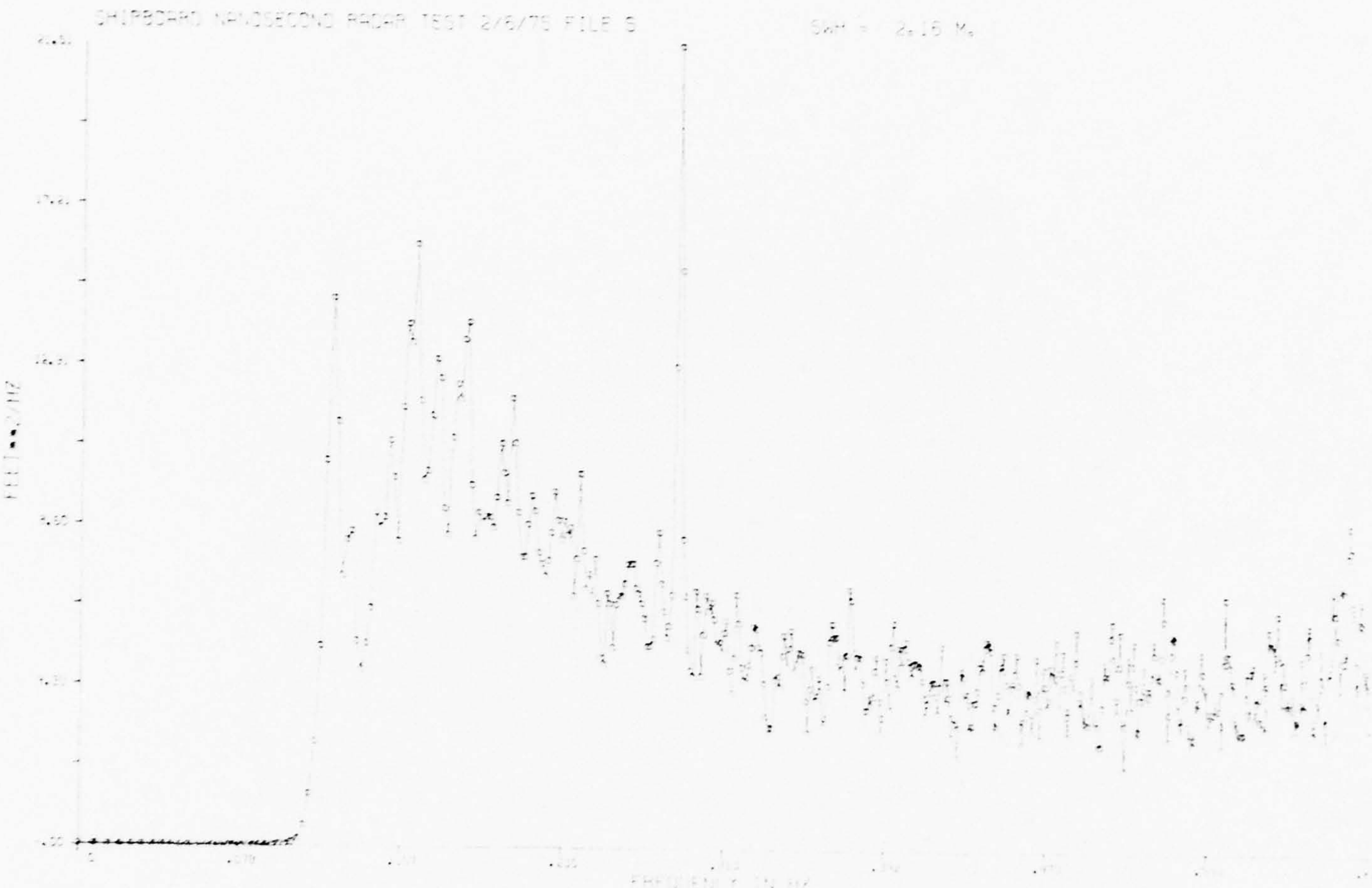

SHIPBOARD NANOSECOND RADAR TEST 2/6/75 FILE 5
SWH = 2.15 M.
FREQUENCY IN HZ

Figure 3-6

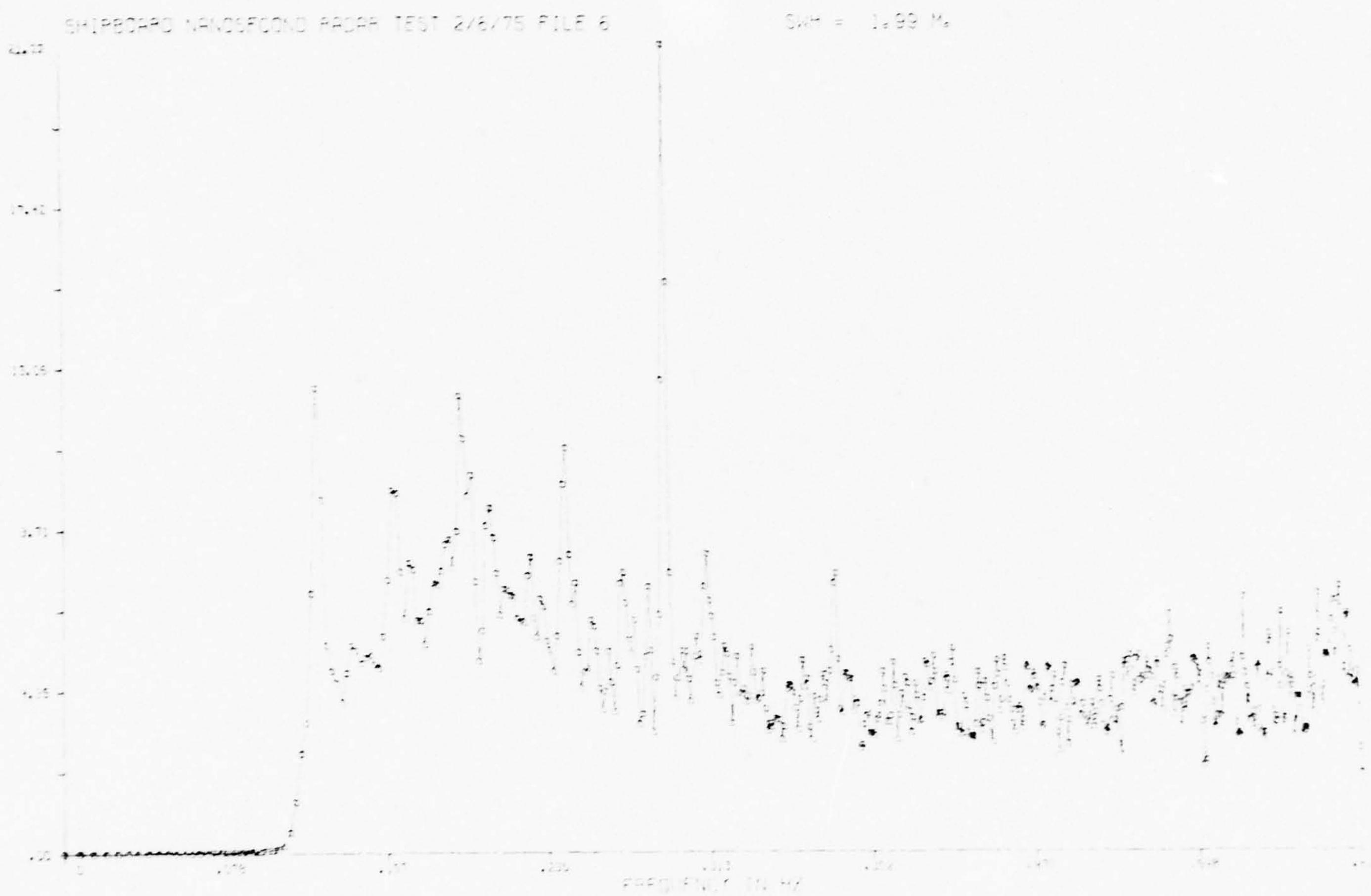

SHIPBOARD NANOSECOND RADAR TEST 2/6/75 FILE 6
SWH = 1.99 M.
FREQUENCY IN HZ

Figure 3-7

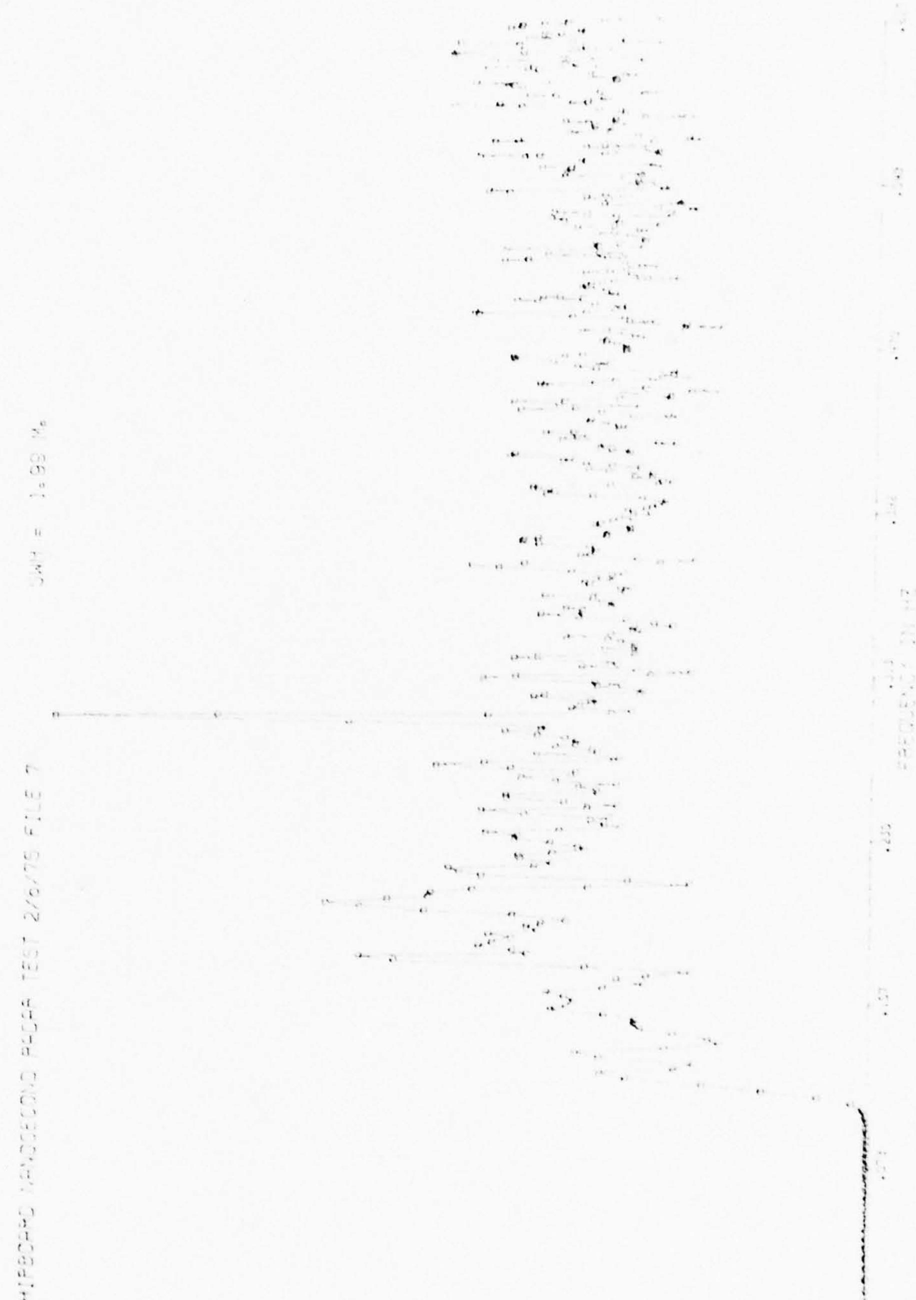


Figure 3-8

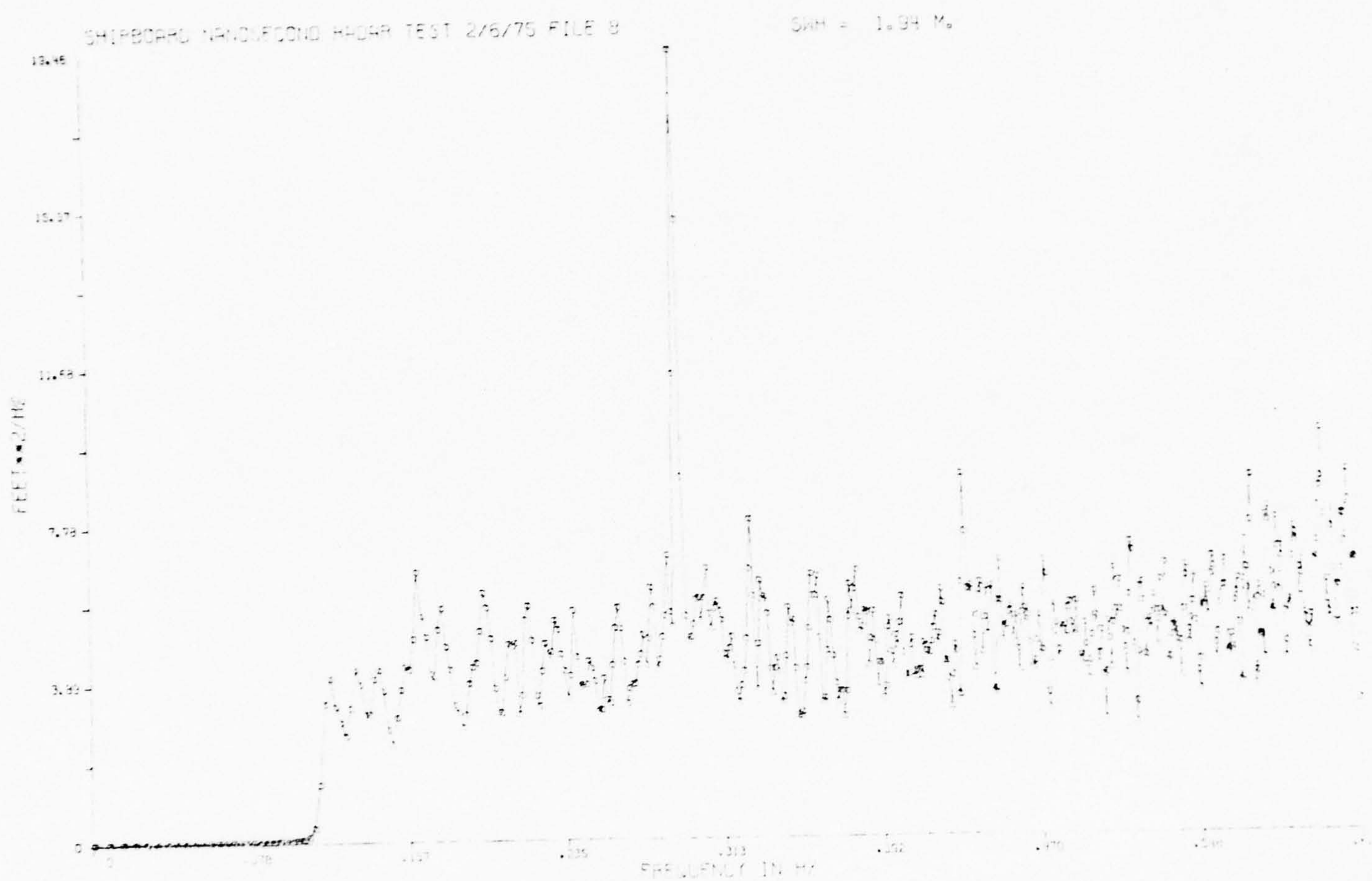

SHIPBOARD NANOSECOND RADAR TEST 2/6/75 FILE 8
SWH = 1.94 M.
FEET**2/HZ
FREQUENCY IN HZ

Figure 3-9

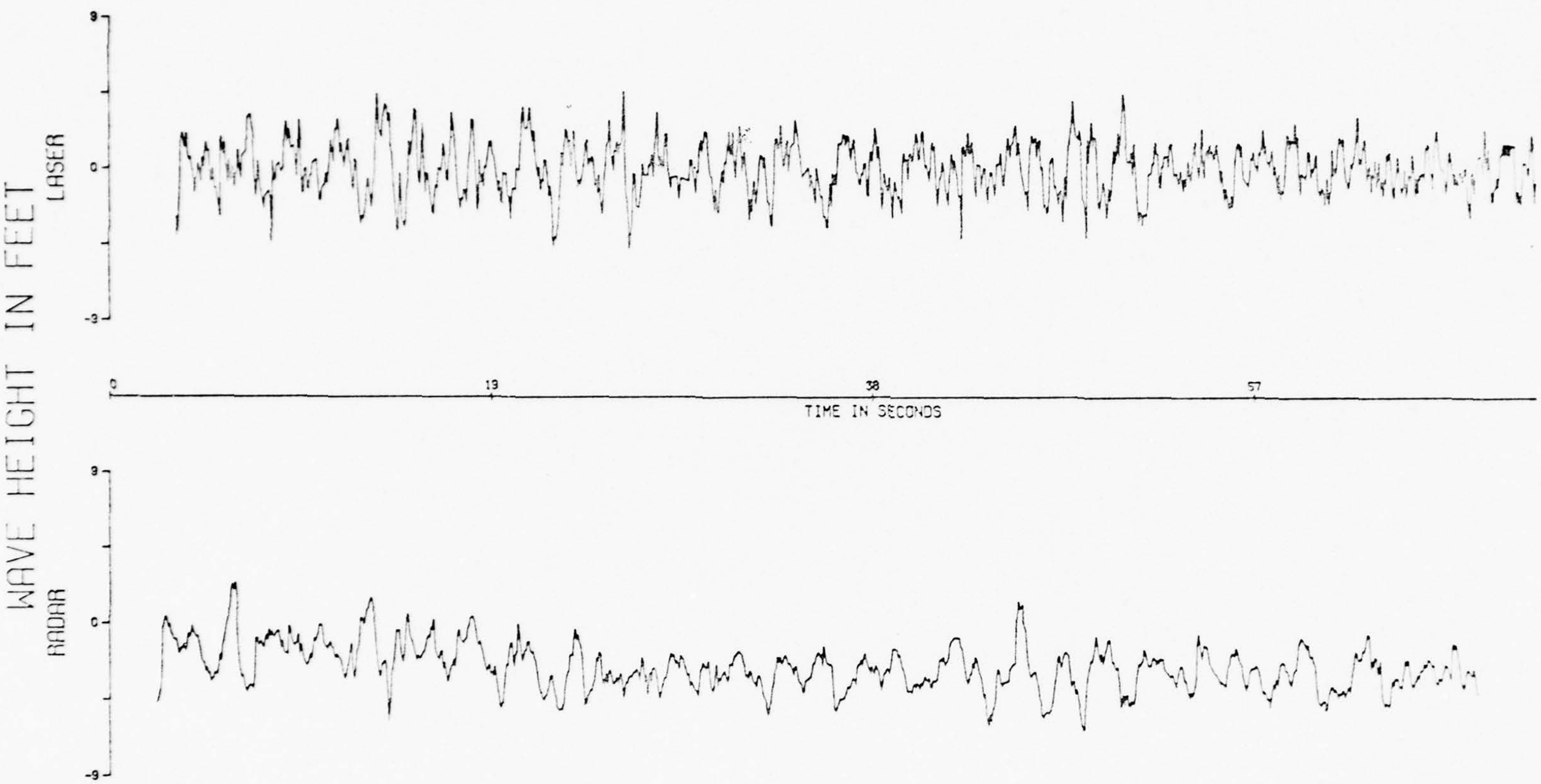

WAVE HEIGHT IN FEET
LASER
3
0
-3
0
19
38
57
TIME IN SECONDS
RADAR
3
0
-3

Figure 3-10

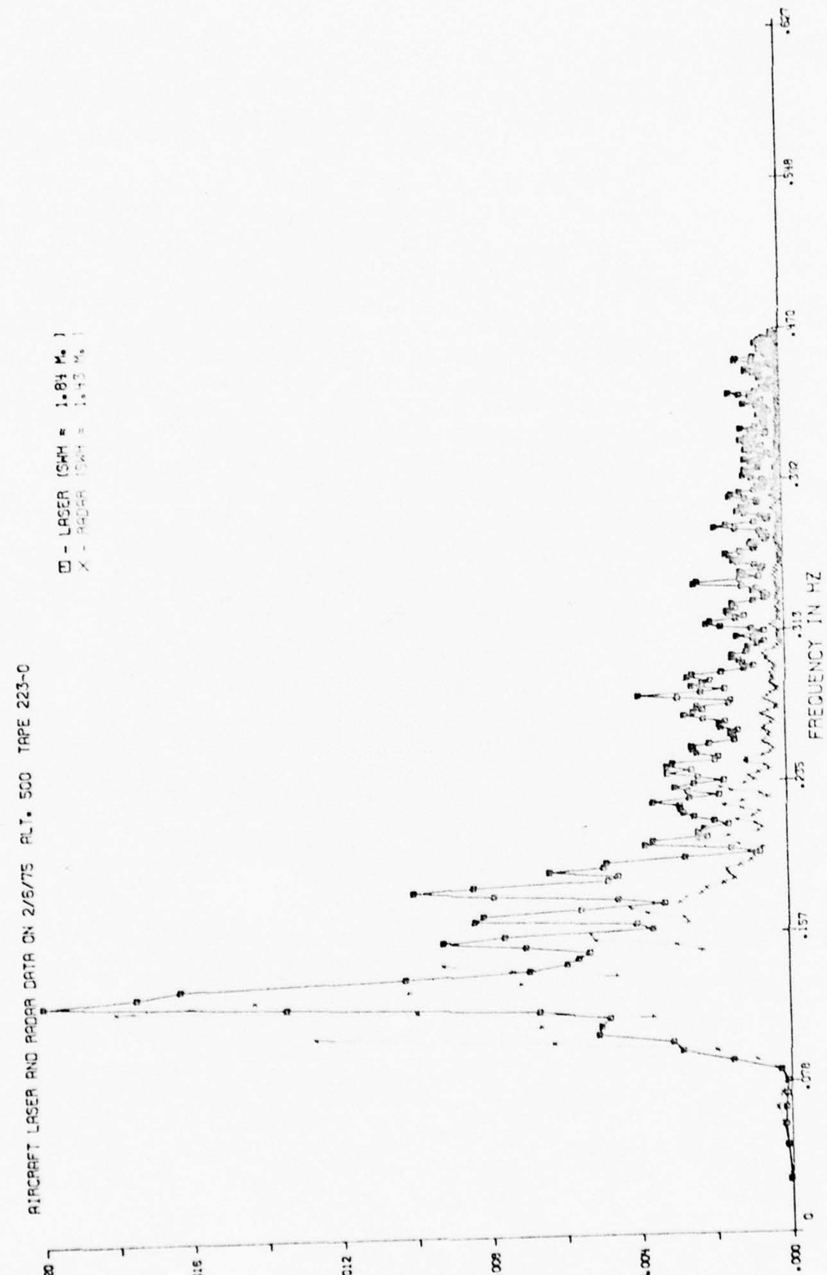
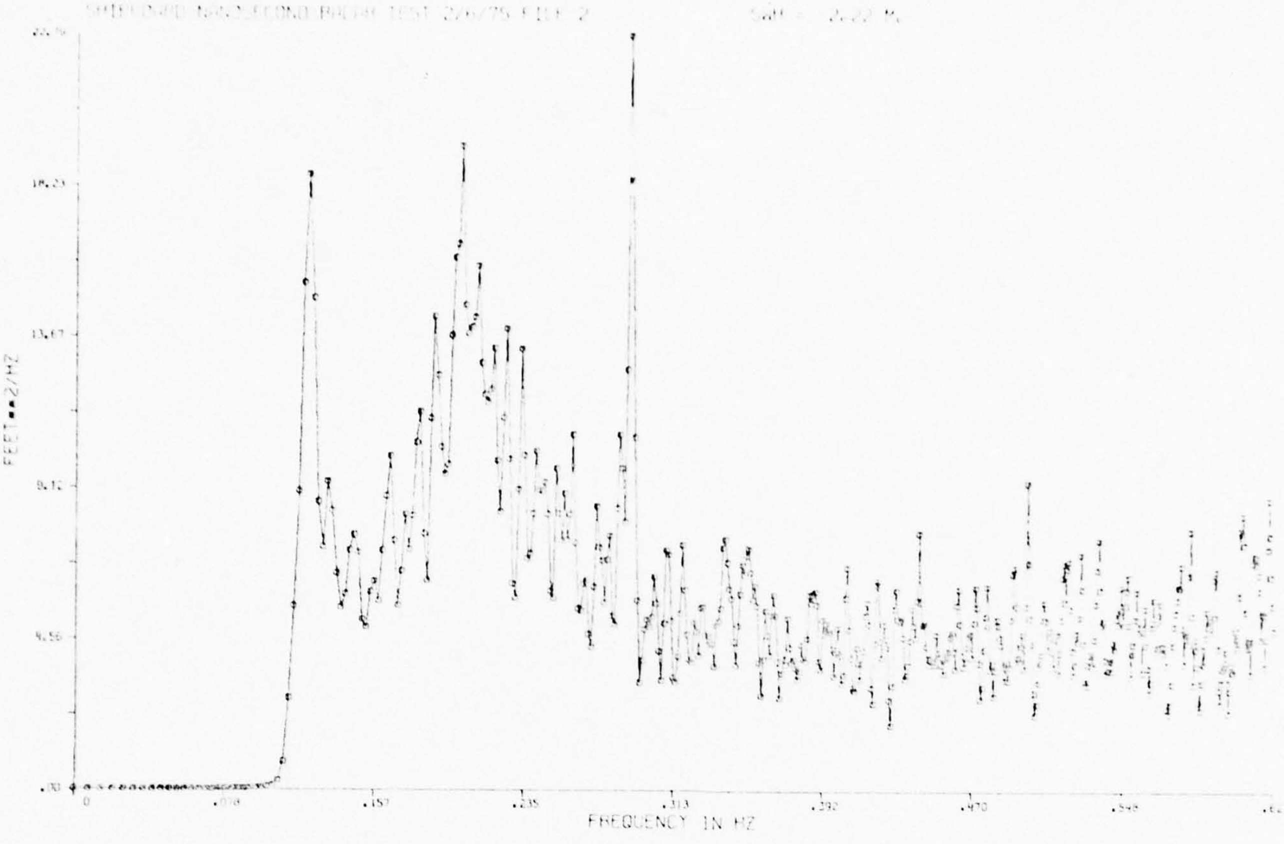

AIRCRAFT LASER AND RADAR DATA ON 2/5/75 ALT. 500 TAPE 223-0
⊡ - LASER (SWH = 1.84 M.)
ASQNU (FEET**2-SEC)
40.020
32.016
24.012
16.008
8.004
.000
0
.078
.157
.235
.313
.392
.470
.548
.627
FREQUENCY IN HZ

Figure 3-11


FEET**2/HZ
18.23
13.67
9.12
4.56
.00
0
.078
.157
.235
.313
.392
.470
.548
.627
FREQUENCY IN HZ

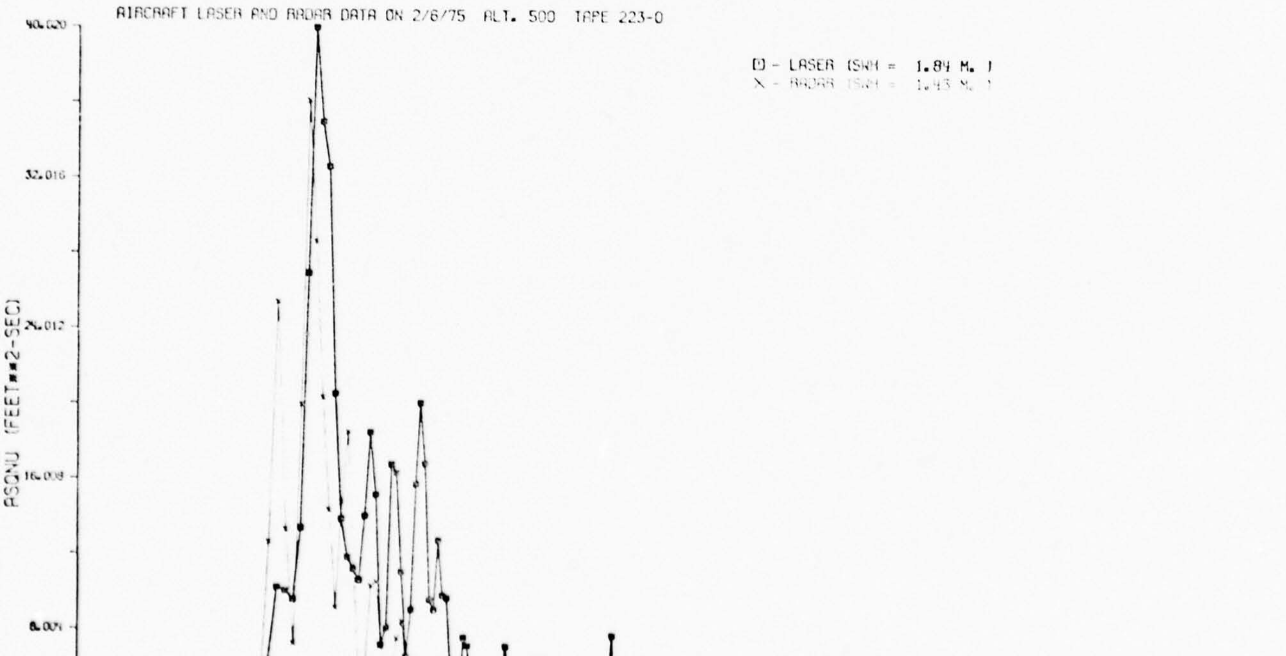

AIRCRAFT LASER AND RADAR DATA ON 2/6/75 ALT. 500 TAPE 223-0
⊡ - LASER (SWH = 1.84 M.)
X - RADAR (SWH = 1.43 M.)
ASQNU (FEET**2-SEC)
40.020
32.016
24.012
16.008
8.004
.000
0
.078
.157
.235
.313
.392
.470
.548
.627
FREQUENCY IN HZ

Figure 3-12

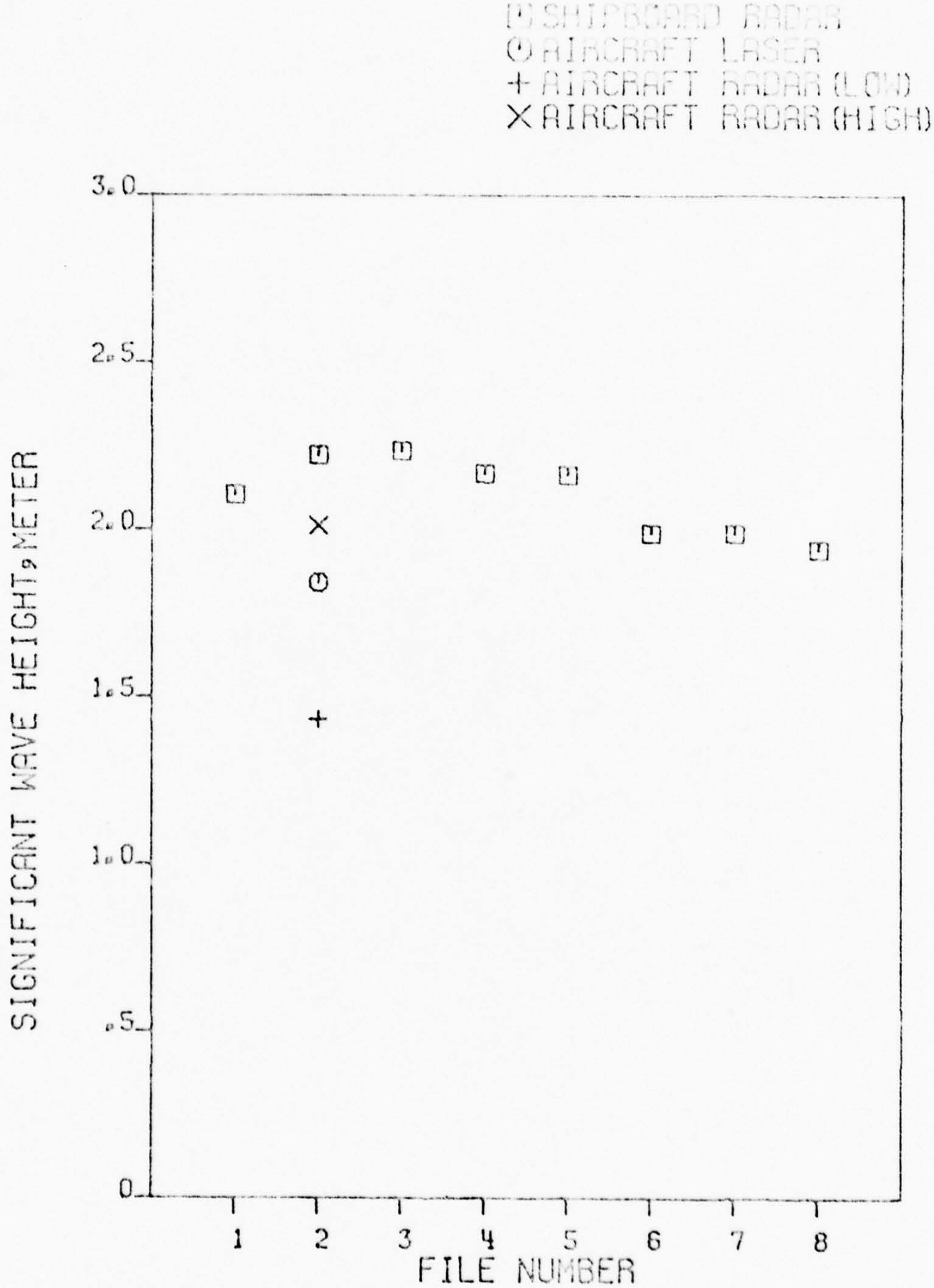

SHIPBOARD RADAR
AIRCRAFT LASER
AIRCRAFT RADAR (LOW)
AIRCRAFT RADAR (HIGH)
3.0
2.5
2.0
1.5
1.0
.5
0.
SIGNIFICANT WAVE HEIGHT, METER
1
2
3
4
5
6
7
8
FILE NUMBER

Figure 3-13

REFERENCES

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APPENDIX A

HIGH PASS DIGITAL FILTER

Formula for the high pass filter is given by Marcel Martin in the reference by Linnette [11]. The filter used to remove the effects of $\Delta R(t) - D$ is:

$$R_f(r) = W_o + 2 \sum_{k=1}^{N} W_k \cos (2\pi kr) \qquad \text{(A-1)}$$

(see reference [11]) where

R_f = filter function,

r = normalized frequency which is defined by f/f_s ,

f = frequency in Hz,

f_s = sampling frequency in Hz,

W_k = the kth weighting function,

N = an integer; total number of weights is defined as $2N + 1$.

The following are used for evaluating the terms in Equation (A-1):

$$W_k = p_k + \frac{\Lambda}{2N + 1} \qquad \text{(A-2)}$$

$$p_k = \left[\frac{\cos(2\pi kh)}{1 - 16h^2k^2}\right]\left[\frac{\sin 2\pi k(r_c + h)}{\pi k}\right] \tag{A-3}$$

$$A = 1 - [p_o + 2 \sum_{k=1}^{N} p_k] \tag{A-4}$$

$$p_o = 2(r_c + h) \tag{A-5}$$

$$r_c = \frac{f_c}{f_s} \tag{A-6}$$

where f_c is the ideal cutoff frequency of the filter in Hz, r_c is the normalized ideal cutoff frequency and h is the slope of the filter fall off. The filter in Equation (A-1) is designed to satisfy the following requirements:

1. the phase shift must be identically zero for all frequencies,
2. (2N + 1) weights are to be used with $W_k = W_{-k}$,
3. unity gain from zero to the ideal cutoff frequency,
4. the weight calculations are optimized to achieve the conditions of a, b, and c in a least square manner with the desired filter-frequency response and considering the following:
   a. the weighting must minimize the oscillations beyond the first zero crossing of the filter frequency-response. This is accomplished by utilizing sine function characterized by the parameter h. By selecting h sufficiently

large, the oscillations cannot exceed the preselected filter frequency fall off. However by increasing the value of h, decreases the sharpnees of the cutoff, but the sharpness of the cutoff decreases as h increases.

b. a second iteration is made on the weight determination to insure that the filter has unit gain at zero frequency.

Since the filter must reject frequencies lower than 0.2 Hz in order to reduce the influence of $\Delta R(t) - \dot{D}$ in range variations, the following values were used to obtain that cut-off frequency:

$N = 256$

$h = 0.003$

$r_c = 0.025.$

The above values assume a sampling frequency of 8 Hz.

APPENDIX B

DOPPLER SHIFT CORRECTIONS

The changing pitch of the sound from, say, a fire-engine siren as it moves by at high speed is familiar to all; this effect, the Doppler effect, is one of the most obvious influences of relative motion between the source and the medium. Similarly, if a wave train of ocean waves propagating at the surface of the ocean is observed by a radar in motion, a Doppler change of frequency also will result. The Doppler effect is purely a kinematic phenomenon and can be evaluated without resorting to dynamical equations of wave motion. By kinematic argument [12], it can be shown that

$$\sigma_T = \sigma_A + \frac{\sigma_T^2}{g} v \cos\xi \qquad \text{(B-1)}$$

where

σ_T = true wave frequency, $2\pi/T$ or ck_T,

k_T = true wave number, $2\pi/\lambda_T$,

λ_T = true wavelength,

σ_A = apparent wave frequency

k_A = apparent wave number, $2\pi/\lambda_A = (\sigma_T^2/g) = (\sigma_T/v \cos\xi)$,

T = wave period,

λ_A = apparent wave length ,

ξ = angle between the ship's heading and wave propagation direction,

v = speed of the ship,

c = phase speed of wave component,

g = gravitational acceleration.

By employing Equation (B-1) and Jacobian transformation [13] from the apparent wave number domain to true wave frequency domain in Euclidean space yields

$$\phi(\sigma_T) = \frac{2\sigma_T}{g} \left(1 + \frac{1}{2} \frac{g}{\sigma_T \ v \cos\xi}\right) \psi_A \ (k_A) \qquad \text{(B-2)}$$

where

$\phi(\sigma_T)$ = wave frequency spectrum whose argument is wave frequency σ_T, and

$\psi_A(k_A)$ = apparent wave number spectrum and

k_A is $\sigma_T^2/g + \sigma_T/v \cos\xi$.

Since data is already digitized, the equations are modified to take into account that the information is sampled at some rate and not continuous. Thus following changes are incorporated to perform the calculations.

M = total number of lags,

J = lag number,

$\Delta x = v \cos\xi \, \Delta t$ = distance between observations,

Δt = time between observations, then

$$k_A \rightarrow k_A(J) = \frac{J}{M\Delta x} = \frac{\sigma_T^{\,2}(J)}{g} + \frac{\sigma_T(J)}{v \cos\xi}$$

from Equation (A-1), and also

$$\sigma_T \rightarrow \sigma_T(J) = -\frac{g}{2v \cos\xi} + \left[\frac{g^2}{4(v \cos\xi)^2} + \frac{g\pi J}{M\Delta x}\right]^{1/2}$$

from Equation (B-2).

APPENDIX C

```
         IDENT    DUMMY
A        BLOCK
         COMMON   Y(4106),Z(4106)
         ENTRY    DUMMY
DUMMY    SLJ      **
         SLJ      DUMMY
         END
         FINIS
```

```
      PROGRAM SHIPSPEC
      DIMENSION   Y(4106).Z(4106).ASQ2NU(513).FNUHT(513)
      DIMENSION  PLTARRAY(1026).IM(2).U(513).S(129)
      DIMENSION   FILT(257).WEIGT(257).LPHI(10).DFNC(301).IFILT(3)
      DIMENSION   IO(2052).RADRNG(4106).ROLL(4106).X(1026)
      DIMENSION CAL(12).ICHNB(12)
      EQUIVALENCE   (IO.Y(2053)).(RADRNG.Y).(ROLL.Z).(WEIGT.FILT)
      EQUIVALENCE   (X.Z(3081))
      COMMON/A/Y.Z
      COMMON/B/NBUFF(513)
      COMMON/SF/SIZE.DELT.PLTSPACE.PL2SEC
      COMMON/3/DFNC
      COMMON/4/CENTROID.STANDDEV.SKEWNESS.KURTOSIS
      TYPE INTEGER   PUNCH.PAUS.PLTON.TESTMODE
      TYPE INTEGER   RADRNG.ROLL.RECNUMB.RADCAL.ROLCAL.FUNCTION
      TYPE REAL   KURTOSIS.LOOKANG.ORTNA
      DATA (IFILT = 8H     LOW.8H    HIGH.8H      NO)
      DATA ((CAL(I).I=1.12) = 8214.,.4991.,.46.,.10.,.10.,.4(32.1725).8214.,
     1  10.,.5000.,.1.)
C
C     HGHTANT = VERTICAL DISTANCE BETWEEN NANOSECOND RADAR AND STILL
C        SEA LEVEL IN FEET
C     NOS = NUMBER OF SAMPLES
C     IM(1) = NUMBER OF POINTS IN FAST FOURIER TRANSFORM
C     IM(2) = POWER OF 2
C     DELT = SAMPLING TIME INTERVAL IN SECOND
C     VEL = SPEED OF SHIP IN KNOT
C     CUT = CUT-OFF FREQUENCY OF THE FILTER
C     H = SLOPE OF WEIGHT FOR FILTER
C     NUMPT = NUMBER OF POINTS IN FILTER
C     LOWHI = LOW PASS FILTER = 1, HIGH PASS FILTER = 2,
C        NO PASS FILTER = 3
C     NF = NUMBER OF FILES TO SKIP
C     NAVGL =
C     LOOKANG = LOOK ANGLE FOR NANOSECOND RADAR IN DEGREE
C     ORTNA = THE ANGLE BETWEEN INCOMING WIND DIRECTION AND OUTGOING
C        SHIP COURSE IN DEGREE EITHER CLOCKWISE OR COUNTERCLOCKWISE
C     LPHI = TITLE OF THE RUN
C     N1 = NOT TO COMPUTE FILTER = 0, TO COMPUTE FILTER = 1
C     N2 =
C     NSKIP =
C     LASTFILE = LAST FILE NUMBER
C     PAUS = NO MACHINE PAUSE = 0, MACHINE PAUSE = 1
C     PLTON = TO COMPUTE WAVE SPECTRUM = 0, NOT TO COMPUTE WAVE SPECTRUM
C        = 1
C     NRECSKP = NUMBER OF FILES TO SKIP ON OUTPUT TAPE FILES
C     NOWAVPLT = TO HAVE WAVE PLOT = 0, NOT TO HAVE WAVE PLOT = 1
C     NPEN = CODED NUMBER FOR COLOR PENS OF THE PLOTTER
C     NREC = NUMBER OF RECORDS IN THE FILE
C     NWPREC = NUMBER OF WORDS PER RECORD
C     NWPDAT = NUMBER OF WORDS PER INPUT DATA IN ONE ARRAY
C     NDAPCAL = APPROXIMATELY LARGER THAN NUMBER OF DATA PER CALIBRATION
C        LEVEL
C     ICHNB = CHANNEL NUMBER ARRAY
C     CAL = CALIBRATION
C     FUNCTIONS
C       1 = WAVE SPECTRA ANALYSIS
C       2 = WRITE ON TAPE UNIT 6
C       3 = REMOVE SHIPMOTION EFFECTS DUE TO ROLL
C     LI = INPUT DATA TAPE UNIT
C     LO = OUTPUT TAPE UNIT
C     PL2SEC =
```

```
C      PLTSPACE = SPACE INTERVAL FOR PLOT
C      MTREW = TO REWIND OUTPUT TAPE = 1. NOT TO REWIND OUTPUT TAPE = 0
C      QP =
C      TESTMODE =
C      FTRUMAX = HIGHEST FREQUENCY TO BE PLOTTED
C      DSTCNTR = DISTANCE BETWEEN RADAR AND THE CENTER OF THE SHIP
C
 9001 FORMAT (3I5,F10.7,F5.0,2F10.5,4I5,F10.2)
 9002 FORMAT (10A8)
 9003 FORMAT (10I5)
 9004 FORMAT (1H1,20X,62HTHE NEXT FILE WILL BE GOVERENED BY THE FOLLOWIN
     *G CONTROL CARDS,//,10X,19HON CONTROL CARD 1 -,//,5X,3HNOS,3X,
     * 5HIM(1),3X,5HIM(2),6X,4HDELT,6X,1HV,8X,3HCUT,8X,1HH,4X,5HNUMPT,
     * 3X,5HLOWHI,6X,2HNF,3X,5HNAVGL,3X,7HLOOKANG/3I8,F10.7,F8.2,2F10.5,
     * 4I8,F10.2,//,10X,39HON CONTROL CARD 2 - LABEL IN 80 COLUMNS,//,
     *  2X,10A8,//,10X,19HON CONTROL CARD 3 -,//,6X,2HN1,6X,2HN2,3X,
     * 5HNSKIP,* MAXFILE*,3X,5HPAUSE,4X,*PLOT NRECSKP  NO PLT      PEN*
     *//,9I8,//10X,19HON CONTROL CARD 4 -//3X,*NUM REC*3X,*NWPREC   ORIN
     *A    *8X*LI*7X*LO1*3X*PL2 SEC*3X*PLOT2 PT INT*6X,*MTRW*8X,*QP  TEST
     *MODE    FTRUMAX*//2I10,F10.2,2I10,F10.0,F15.8,2(I10,F10.0),//)
 9005 FORMAT (  *0     PARITY ERROR ON ORIG INPUT TAPE*,/)
 9006 FORMAT (1H0)
 9007 FORMAT (21H      MAXIMUM VALUE = ,F8.2,  21H      MINIMUM VALUE = ,
     * F8.2)
 9008 FORMAT (1H1,59X,14HPOWER SPECTRUM//20X,12HTHIS RUN IS ,10A8,/,15X,
     *16HAVG'D SPECTRA  =,I6  ,50X,*DATA FACTOR = *F10.5,/,15X,16HNUMBER
     * OF LAGS =I6,50X,14HCUT           = F9.4,/,15X,16HDELTA TIME     =,
     *F14.7,42X,14HSLOPE         = F9.4,/,15X,16HSHIP VELOCITY  =F11.4,
     * 45X,14HWEIGHTS       = , I4,/,15X,16HVARIANCE       =F11.4,45X,
     *      14HH 1/3        = F9.4,/,49X,A8,14H PASS FILTERED,/)
 9009 FORMAT (* APPARENT    VARIANCE    APPARENT    CIRCULAR   TRUE CIRC
     *    TRUE FREQ   TRUE FREQ   TRUE WAVE   TRUE WAVE     FILTER*/*   FR
     *EQ*18X,*FREQ SPEC      FREQ      FREQ SPEC      (HZ)        SPECTRUM
     *  NUMBER          NUMBER       WEIGHTS*/97X,*SPECTRUM*//)
 9010 FORMAT (* *,F8.3,2F12.4,F12.3,4F12.4,F12.3,F12.4)
 9011 FORMAT (*0 PARITY ERROR ON READ IN*)
 9012 FORMAT (*0*//,5X,*NUM OBS   =*F11.0,/,5X,*CENTROID =*F11.4,/,5X,
     **STD DEV   =*F11.4,/,5X,*SKEWNESS =*F11.4,/,5X,*KURTOSIS =*F11.4)
 9014 FORMAT (I5,F10.2,2I5,F5.0,F10.8,I5,F5.0,I5,F5.0,I5)
 9015 FORMAT (*0*,6F12.4,2F12.6,I10,/,1X,4F12.4,/)
 9016 FORMAT (10X,19HON CONTROL CARD 5 -,//,2X,*FUNCTION*,3X,
     * *ICHNG*//6X,I2,5X,12(I2,1X),//)
 9017 FORMAT (13I2)
C
      PAUSE 1
      CALL PLOTS(PLTARRAY,1026,1)
      NEOF = IM2PREV = IFILELO = IFILENUM = 0
      PI = 3.141592654
      DTR = PI/180.
      TWOPI = 2. * PI
      TWOPISQ = TWOPI ** 2
      G = 32.1725
      GXPI = G*PI
      TWOOVG = 2.0/G
      GOVTWO = G/2.
      HGHTANT = 76.
      DSTCNTR = 40.
      NWPREC = 513
      NWPDAT = 3
      NOAPCAL = 30
C
C      READ IN CONTROL CARDS
C
  100 READ (2,9001)NOS,IM(1),IM(2),DELT,VEL,CUT,H,NUMPT,LOWHI,NF,NAVGL,
     * LOOKANG
      IF (EOF,2 ) 9000,200
```

```
  200 II = 0
      READ (2,9002)LPHI
      READ (2,9003)N1,N2,NSKIP,LASTFILE,PAUS,PLTON,NRECSKP,NOWAVPLT,NPEN
      READ (2,9014)NREC,ORTNA           ,LI,LO,PL2SEC,PLTSPACE,MTREW,QP,
     * TESTMODE,FTRUMAX
      READ (2,9017) FUNCTION,(ICHNB(I),I = 1,12)
      I2 = IM(1)
      I3 = I2/2
      I4 = I3+1
      THETA = LOOKANG*DTR
      ORINAR=ORINA*DTR
      R0 = HGHTANT/COS(THETA)
      IF(IM(2) .NE. IM2PREV)    225,250
  225 IFS = -1
      IM2PREV = IM(2)
C
C     NF = 0 IF NO FILES ARE TO BE SKIPPED ON INPUT TAPE
C
  250 DO 300    I = 1,NF
      CALL SKIPFILE(LI)
      IFILENUM = IFILENUM + 1
  300 CONTINUE
      LOLGTH = 2*NUMPT
      IF(LOLGTH .GT. 512)    400,450
  400 LOLGTH = 512
  450 LOINST = LOLGTH - 1
      LILGTH= NOS/8
      LIINST=LILGTH-1
      LILILGTH = 2*LILGTH
      NDATPREC = NWPREC/NWPDAT
      NLBUFF = NOS/NDATPREC
      NPBUFF = NREC/NLBUFF
      NMAXCALB = NDAPCAL+20
      NZCAL = NOS-7
C
C     CONVERT SHIP VELOCITY FROM KNOTS TO FEET/SEC.
C
      V = VEL*1.6878*COS(ORINAR)
C
C     SKIP NRECSKP FILES ON OUTPUT TAPE
C
      DO 500    I = 1,NRECSKP
      CALL SKIPFILE(LO)
      IFILFLO = IFILFLO + 1
  500 CONTINUE
      IF (V   .EQ.   0.) 502,501
  501 CONST = G/(2.*V)
      CONSQ = CONST*CONST
      DX = ABSF(V*DELT)
  502 NUMPTP1 = NUMPT + 1
      SCSQ = 1
      SIZE = NUMPT
      NAVG = 0
      AVGY = AVGRNG = 0.
C
C     PRINT OUT CONTROL CARDS
C
  510 PRINT 9004,    NOS,IM(1),IM(2),DELT,VEL,CUT,H,NUMPT,LOWHI,NF,NAVGL,
     *LOOKANG,LPHI,N1,N2,NSKIP,LASTFILE,PAUS,PLTON,NRECSKP,NOWAVPLT,NPEN
     *,NREC,NWPREC,ORINA  ,LI,LO,PL2SEC,PLTSPACE,MTREW,QP,TESTMODE,
     * FTRUMAX
      PRINT 9016,  FUNCTION,(ICHNB(I),I = 1,12)
      NTOT = IM(1)
      RECNUMB = FNTOT = 0.
      DO 520    I = 1,301
  520 DENC(I) = 0.
```

```
      DO 530   I = 1,14
  530 ASQ2NU(I) = 0.
C
C     TEST IF FILTER IS TO BE COMPUTED.  IF(NUMPT .GT. 0) = YES
C
      IF(NUMPT .EQ. 0  .OR.  NI .EQ. 0)     900,550
C
C     COMPUTE FILTER
C
C     NUMPT = NUMBER OF POINTS OVER WHICH THE AVERAGE IS TO BE TAKEN
C     CUT   = CUT OFF FREQUENCY
C     H     = SLOPE OF WEIGHTS
C
  550 KA = NUMPT + 1
      CTH = CUT + H
      FILT(KA) = 2.*CTH
      SUMK = 0.
      DO 700   I = 1,NUMPT
      P = I
      QQ = 1. - (16.*H*H*P*P)
      IF(QQ .NE. 0.)    600,575
  575 FILT(I) = 0.
      GO TO 700
  600 FILT(I) = (COSF(TWOPI*P*H)*SINF(TWOPI*P*CTH))/(PI*P*QQ)
      SUMK = SUMK + FILT(I)
  700 CONTINUE
      FLJO = (1. - (FILT(KA) + 2.*SUMK))/(2.*NUMPT + 1.)
      DO 800   I = 1,KA
      WEIGT(I) = FILT(I) + FLJO
  800 CONTINUE
      NI = 0
  900 CONTINUE
      YMAX = ZMAX = PREVMAX = -10000.
      YMIN = ZMIN = PREVMIN =  10000.
C
C     READ IN DATA
C
      NSPECAVG = 0
      I1 = 1
      I2 = IM(1)
      I4 = I2/2 + 1
      I6 = I4 - 1
      NS = I4
      FREQRES = 1./(2.*DELT*IM(1))
      FACU = DELT*IM(1)/TWOPI
      IOST = 1
      YPREV = -1000.
      IF(IFILENUM .EQ. 13)   910,925
  910 IOST = 2501
  925 ISTRT = 1
      DO 1075 I=1,NLBUFF
      BUFFER IN(LI,1) (NBUFF(1),NBUFF(NWPREC))
  950 IF(UNIT,LI)     950,1050,2325,1000
 1000 PRINT 6005
 1050 CALL UNPKSHIP(ICHNB,I)
 1075 CONTINUE
      RECNUMB = RECNUMB + 1
      NEOF = 0
      IF(RECNUMB .GT. 1)    1400,1100
C     CALCULATING CALIBRATION
 1100 J=0
      YSUM = YSUMSQ = ZSUM = ZSUMSQ = 0.
      RADCALV = ROLCALV = RADCALSD = ROLCALSD =0.
      NCHCAL = 0
      DO 1275   I = IOST,4097
      YSUM = YSUM + RADNG(I)
```

```
      ZSUM = ZSUM + ROLL(I)
      YSUMSQ = YSUMSQ + RADRNG(I)*RADRNG(I)
      ZSUMSQ = ZSUMSQ + ROLL(I)*ROLL(I)
      IF(I .LT. 10)     1275,1150
 1150 YZERO = YSUM/I
      ZZERO = ZSUM/I
      YSTD = SQRTF((YSUMSQ - I*YZERO*YZERO)/(I-1))
      ZSTD = SQRTF((ZSUMSQ - I*ZZERO*ZZERO)/(I-1))
      YTEST = 3.*YSTD
      ZTEST = 3.*ZSTD
      YP1 = RADRNG(I+1) - YZERO
      ZP1 = ROLL(I+1) - ZZERO
      YP20 = RADRNG(I+4)  - YZERO
      ZP20 = ROLL(I+4)  - ZZERO
      YP40 = RADRNG(I+7)  - YZERO
      ZP40 = ROLL(I+7)  - ZZERO
      IF(ABS(YP1) .GT. YTEST  .AND.  ABS(ZP1) .GT. ZTEST)  1175,1180
 1175 IF(ABS(YP20) .GT. YTEST  .AND.  ABS(YP40) .GT. YTEST  .AND.
     *   ABS(ZP20) .GT. ZTEST  .AND.  ABS(ZP40) .GT. ZTEST)   1300,1200
 1180 IF (ABS(YP1)  .GT.  YTEST) 1200,1225
 1200 RADRNG(I+1) = RADRNG(I)
 1225 IF(ABS(ZP1) .GT. ZTEST)   1250,1275
 1250 ROLL(I+1) = ROLL(I)
 1275 CONTINUE
      RECNUMB = 0
      GO TO 925
 1300 IJ = I+1
      JK = 0
      RADCALV1 = RADCALS1 = ROLCALV1 = ROLCALS1 = 0.
      DO 1315 K = IJ,NZCAL
      YPCALC = RADRNG(K+1)-YZERO
      ZPCALC = ROLL(K+1)-ZZERO
      IF (ABS(YPCALC)  .GT.  YTEST  .AND.  ABS(ZPCALC)  .GT. ZTEST)
     *    1305,1320
 1305 IF (K  .GT. I+2) 1310,1315
 1310 JK = JK+1
      RADCALV1 = RADCALV1+RADRNG(K)
      RADCALS1 = RADCALS1+RADRNG(K)*RADRNG(K)
      ROLCALV1 = ROLCALV1+ROLL(K)
      ROLCALS1 = ROLCALS1+ROLL(K)*ROLL(K)
 1315 CONTINUE
 1320 RADCALV2 = RADCALV1/JK
      ROLCALV2 = ROLCALV1/JK
      RADCALS2 = SQRTF((RADCALS1-JK*RADCALV2*RADCALV2)/(JK-1))
      ROLCALS2 = SQRTF((ROLCALS1-JK*ROLCALV2*ROLCALV2)/(JK-1))
      IF (RADCALS2  .GT.  3.*YSTD  .OR.  ROLCALS2  .GT.  3.*ZSTD)
     *    1321,1325
 1321 IF (NCHCAL  .GT.  0) 1326,1180
 1325 J = J+JK
      RADCALV = RADCALV+RADCALV1
      RADCALSD = RADCALSD+RADCALS1
      ROLCALV = ROLCALV+ROLCALV1
      ROLCALSD = ROLCALSD+ROLCALS1
 1326 IJ = K+1
      NCOUNT = 0
      NCHCAL = 1
      DO 1340 I = IJ,NZCAL
      YP1 = RADRNG(I+1)-YZERO
      ZP1 = ROLL(I+1)-ZZERO
      YP20 = RADRNG(I+4)-YZERO
      ZP20 = ROLL(I+4)-ZZERO
      YP40 = RADRNG(I+7)-YZERO
      ZP40 = ROLL(I+7)-ZZERO
      NCOUNT = NCOUNT + 1
      IF (NCOUNT  .GT.  [illegible]) [illegible],1327
 1327 IF (ABS(YP1)  .GT.  YTEST  . AND.  ABS(ZP1)  .GT.  ZTEST)
```

```
     *    1330,1340
1330 IF (ABS(YP20)  .GT.  YTEST  .AND.  ABS(YP40)  .GT.  YTEST
     *   .AND.  ABS(ZP20)  .GT.  ZTEST  .AND.  ABS(ZP40)  .GT.  ZTEST)
     *    1300,1340
1340 CONTINUE
1345 RADCALV = RADCALV/J
     ROLCALV = ROLCALV/J
     RADCALSD = SQRTF((RADCALSD -  J *RADCALV*RADCALV)/(J-1))
     ROLCALSD = SQRTF((ROLCALSD -  J *ROLCALV*ROLCALV)/(J-1))
1350 RACALCNT = RADCALV - YZERO
     ROCALCNT = ROLCALV - ZZERO
     MCHECK = 0
     DO 1380 ICH = 1,12
     ICHECK = ICHNB(ICH)
     IF (ICHECK .EQ. 0) 1380,1355
1355 MCHECK = MCHECK+1
     IF (MCHECK .EQ. 1) 1360,1370
1360 ICH1 = ICHECK
     GO TO 1380
1370 ICH2 = ICHECK
1380 CONTINUE
     AMPTEST = CAL(ICH1)/1.0
     DFRAD = CAL(ICH1)/RACALCNT
     DFROL = CAL(ICH2)/ROCALCNT
     ISTRT = ((I+480)/LILGTH + 1)*LILGTH
     ISTRT = LILGTH - MOD(ISTRT,LTLILGTH) +ISTRT + 1
     PRINT 9015,   YZERO,ZZERO,RADCALV,ROLCALV,RACALCNT,ROCALCNT,DFRAD,
    * DFROL,ISTRT,YSTD,ZSTD,RADCALSD,ROLCALSD
1400 DO 1500   I = ISTRT,NOS
     Y(I) = DFRAD*(RADRNG(I) - YZERO)
     IF(YPREV .EQ. -1000.)   1475,1425
1425 IF(ABSF(Y(I) - YPREV) .GT. AMPTEST)   1450,1475
1450 Y(I) = YPREV
1475 YPREV = Y(I)
1500 Z(I) = DFROL*(ROLL(I) - ZZERO)
C       DEDUCT SHIPMOTION EFFECTS DUE TO ROLL
     IF (FUNCTION .EQ. 3) 1510,1530
1510 DO 1520 I = ISTRT,NOS
     ZRADIAN = DTR * Z(I)
     VDSTRAD = HGHTANT - DSTCNTR *  TAN(ZRADIAN)
     THETADF = ZRADIAN - THETA
     RADMNRNG = VDSTRAD *  COS(ZRADIAN)/ COS(THETADF)
1520 Y(I) = Y(I) -RADMNRNG
C       MESSAGE INPUT CALIBRATED DATA
1530 DO 2300   I = ISTRT,NOS ,LILGTH
     NTIMES = 0
     JEND = I + LIINST
1525 MAXPT = MINPT = AVGRNG = 0
     YMAX = -10000.
     YMIN =  10000.
     DO 1900   J = I,JEND
     IF(Y(J) .GT. YMAX)   1550,1600
1550 YMAX = Y(J)
     MAXPT = J
     GO TO 1700
1600 IF(Y(J) .LT. YMIN)   1650,1700
1650 YMIN = Y(J)
     MINPT = J
1700 IF(Z(J) .GT. ZMAX)   1750,1800
1750 ZMAX = Z(J)
     GO TO 1900
1800 IF(Z(J) .LT. ZMIN)   1850,1900
1850 ZMIN = Z(J)
1900 AVGRNG = AVGRNG + Y(J)
     RNGAVG = AVGRNG/LOLGTH
1950 IF((ABS(MAXPT - MINPT) .GT. 3)   2050,2000
```

```
2000 IF(MAXPT .GT. MINPT)    2020,2030
2020 Y(MAXPT) = Y(MAXPT+1)
     Y(MINPT) = Y(MINPT-1)
     GO TO 1525
2030 Y(MAXPT) = Y(MAXPT-1)
     Y(MINPT) = Y(MINPT+1)
     GO TO 1525
2050 IJUMP = 0
     NTIMES = NTIMES + 1
     IF(NTIMES .GT. 2)    2200,2075
2075 TESTYMAX = (YMAX - RNGAVG)*0.6
     TESTYMIN = (YMIN - RNGAVG)*0.6
     IF(Y(MAXPT-1) - RNGAVG .GT. TESTYMAX  .OR.  Y(MAXPT+1) - RNGAVG
    * .GT. TESTYMAX)    2125,2100
2100 Y(MAXPT) = (Y(MAXPT-1) + Y(MAXPT+1))/2.
     IJUMP = 1
2125 IF(Y(MINPT-1) - RNGAVG .LT. TESTYMIN  .OR.  Y(MINPT+1) - RNGAVG
    * .LT. TESTYMIN)    2175,2150
2150 Y(MINPT) = (Y(MINPT-1) + Y(MINPT+1))/2.
     IJUMP = 1
2175 IF(IJUMP .EQ. 1)    1525,2200
2200 IF(UNIT,LO)    2200,2250
2250 BUFFER OUT (LO,1)(Y(I),Y(JEND))
     IF(YMAX .GT. PREVMAX)    2260,2270
2260 PREVMAX = YMAX
2270 IF(YMIN .LT. PREVMIN)    2280,2290
2280 PREVMIN = YMIN
2290 AVGY = AVGY + AVGRNG
     NAVG = NAVG + LOLGTH
2300 CONTINUE
     IF(IFILENUM.EQ.LASTFILE.AND.RECNUMB.EQ.3)2325,925
2325 NEOF = NEOF + 1
     IFILENUM = IFILENUM + 1
     YMAX = PREVMAX
     YMIN = PREVMIN
     IF(NEOF .GE. 2)    9999,2400
2400 PRINT 9007,    YMAX,YMIN
     PRINT 9007,    ZMAX,ZMIN
     PRINT 9006
     ENDFILE LO
     IFILELO = IFILELO + 1
C    OUTPUT TAPE IS READY
     IF(MTREW .EQ. 0)    2500,2450
2450 REWIND LI
     IFILENUM = 0
2500 IF (FUNCTION . EQ. 2) 2510,2530
2510 PAUSE
     GO TO 100
2530 CALL BACKFILE(LO)
     CALL BACKFILE(LO)
     IF(IFILELO .LE. 1)    2700,2600
2600 CALL SKIPFILE(LO)
2700 LABEL = 0
     IFIRST = 1
     AVGY = AVGY/NAVG
     NRECSTRT = 1
     IM1 = IM(1)
     NUMREC = LOLGTH + IM1
2800 DO 2860    I = NRECSTRT,NUMREC,LOLGTH
     IA = I
     IB = I + LOINST
     BUFFER IN (LO,1)(Y(IA),Y(IB))
2810 IF(UNIT,LO)    2815,2860,4130,2820
2820 PRINT 9005
2860 CONTINUE
     DELTY = ZMAX - ZMIN = 0.
```

```
C
C       IF (PLTON .GT. 0)  DO NOT COMPUTE SPECTRA
C
 2926 IF(PLTON .GT. 0)    2930,2940
 2930 NCOPYST = IMI + 1
      J = 1
      DO 2935    I = NCOPYST,NUMREC
      Y(J) = Y(I)
 2935 J = J + 1
      NRECSTRT = J
      GO TO 2800
C
C       APPLY FILTER TO DATA (0 = NO)
C
 2940 IF(NUMPT .EQ. 0)    3600,2950
 2950 DO 3200    I = 1,IMI
      KB = I + NUMPT
      SUMCK = WEIGT(KA)*Y(KB)
      DO 2960    J = 1,NUMPT
      IA = NUMPT + 1 - J
      IB = IA + NUMPT + I
      IC = J - 1 + I
      SUMCK = SUMCK + WEIGT(IA)*(Y(IC) + Y(IB))
 2960 CONTINUE
C
C       LOWHI =
C       1 =  LOW PASS FILTER
C       2 = HIGH PASS FILTER
C       3 = NOPASS FILTER
C
      IF(LOWHI .EQ. 1)    3100,3000
 3000 SUMCK = Y(KB) - SUMCK
 3100 Z(I) = SUMCK
      DCLEV = DCLEV + Z(I)
 3200 CONTINUE
      DCLEV = DCLEV/IMI
C     DEDUCT STEADY STATE TERM AND CALCULATE WAVE HEIGHT DISTRIBUTION
C        FUNCTION
 3600 DO 3670    M = 1,IMI
 3610 X(M) = Z(M) - DCLEV
      IF(X(M) .GT. ZMAX)    3612,3614
 3612 ZMAX = X(M)
      GO TO 3620
 3614 IF(X(M) .LT. ZMIN)    3616,3620
 3616 ZMIN = X(M)
 3620 CONTINUE
      INDEX=X(M)*4.+151.5
      IF (INDEX  .LT.  1) 3640,3650
 3640 INDEX=1
      GO TO 3670
 3650 IF(INDEX .GT. 301)    3660,3670
 3660 INDEX = 301
 3670 DENC(INDEX)    = DENC(INDEX)    + 1
      PRINT 9007,    ZMAX,ZMIN
      IF(NOWAVPLT .GT. 0)    3800,3700
 3700 CALL PLOT2(IFIRST,IMI,YMIN,YMAX,ZMIN,ZMAX,LABEL)
      LABEL = 1
 3800 CONTINUE
      FNTOT = FNTOT + IMI
      CALL FOURIER (X,S,IM(2),IFS)
      IFS = -2
C     SMOOTHING BY HAMMING FUNCTION
 3850 DO 3900    J = 1,I4
 3900 X(J) = X(2*J-1)**2 + X(2*J)**2
      U(1) = 0.54*X(1) + 0.46*X(2)
      DO 4000    J = 2,I6
```

```
4000 U(J) = 0.23*(X(J-1) + X(J+1)) + 0.54*X(J)
     U(14)= 0.54*X(14) + 0.46*X(16)
     DO 4050   I = 1,14
4050 ASQ2NU(I)    = ASQ2NU(I)    + U(I)
     NSPECAVG = NSPECAVG + 1
     GO TO 2930
4130 IF(NOWAVPLT .GT. 0)   4180,4160
4160 IFIRST = NTOT
     CALL PLOT2(IFIRST,NTOT,YMIN,YMAX,ZMIN,ZMAX,LABEL)
     IF(PLTON .GT. 0)   6500,4180
4180 SPECTAVG = 2*NSPECAVG
     EMAX     = 0.
     DO 4200   I = 1,14
     U(I)   =ASQ2NU(I)   /SPECTAVG
     EMAX     = EMAX     + U(I)
4200 CONTINUE
     HBAR     = 4.0*SQRTF(EMAX)
     IF(NUMPT .EQ. 0)   4205,4210
4205 LOWHI = 3
C
C    WRITE HEADINGS
C
4210 PRINT 9008,    LPHI,NSPECAVG,DFRAD,IM(1),CUT,DELT,H,V,NUMPT,EMAX,
    * HBAR,IFILT(LOWHI)
     PRINT 9009
C
C    OUTPUT LOOP
C
C    REMOVE DOPPLER EFFECT
     DO 4300   I = 1,14
     R = 2*(I-1)
     FTRU = R*FREQRES
     IF (V  .EQ.  0.) 4215,4213
4213 FMUHT = SQRTF(CONSQ + GXPI*R/(IM(1)*DX)) - CONST
     IF (I  .EQ.  1) 4214,4220
4214 FMUHT = 0.
     GO TO 4220
4215 FMUHT = FTRU * TWOPISQ
4220 FNUHT(I) = FMUHT/TWOPI
     FKT = (FMUHT**2)/G
     ASQ1 = U(I)   *FACU
     IF (V  .EQ.  0.) 4222,4221
4221 ASQMU1= ABSF(TWODVG*(FMUHT + CONST)*ASQ1*V)
     GO TO 4223
4222 ASQMU1 = ASQ1
4223 ASQKT1 = 0.
     IF(FMUHT .NE. 0.)   4225,4230
4225 ASQKT1 = ASQMU1*GDVTWO/FMUHT
4230 ASQ2NU(I)    = TWOPI*ASQMU1
     IF(FTRU .GT. FTRUMAX)   4300,4240
4240 IF(I .GT. KA)        4275,4250
4250 PRINT 9010,    FTRU,U(I),ASQ1,FMUHT,ASQMU1,FNUHT(I),ASQ2NU(I),FKT,
    * ASQKT1,WEIGT(I)
     GO TO 4300
4275 PRINT 9010,    FTRU,U(I),ASQ1,FMUHT,ASQMU1,FNUHT(I),ASQ2NU(I),FKT,
    * ASQKT1
4300 CONTINUE
C    CALCULATE WAVE HEIGHT DISTRIBUTION FUNCTION FOR PLOT ONLY
4310 DO 4325   M = 5,301
     IF(DENC(M)   .GT. 0.)   4350,4325
4325 CONTINUE
4350 IST     = M-XMODF(M,4)   + 1
     DO 4375   MM = 4,301
     M = 301 - MM
     IF(DENC(M)   .GT. 0)   4400,4375
4375 CONTINUE
```

```
4400 IND     = M + 1 -XMODF(M,4)
     CENTROID = STANDDEV = SKEWNESS = KURTOSIS = FNUMB = 0.
     DEV = (IST     - 151)/4.
     DO 5000   M = IST,IND
     CENTROID = CENTROID + DENC(M)   *DEV
     STANDDEV = STANDDEV + DENC(M)   *DEV**2
     SKEWNESS = SKEWNESS + DENC(M)   *DEV**3
     KURTOSIS = KURTOSIS + DENC(M)   *DEV**4
     FNUMB = FNUMB + DENC(M)
5000 DEV = DEV + 0.25
     CENTROID = CENTROID/FNUMB
     STANDDEV = STANDDEV/FNUMB
     SKEWNESS = SKEWNESS/FNUMB
     KURTOSIS = KURTOSIS/FNUMB
     KURTOSIS = KURTOSIS - 4.*CENTROID*SKEWNESS + 6.*CENTROID*CENTROID*
    * STANDDEV - 3.*CENTROID**4
     SKEWNESS = SKEWNESS - 3.*CENTROID*STANDDEV + 2.*CENTROID**3
     VARIANCE = STANDDEV - CENTROID*CENTROID
     STANDDEV = SQRTF(VARIANCE)
     SKEWNESS = SKEWNESS/(STANDDEV*VARIANCE)
     KURTOSIS = KURTOSIS/(VARIANCE*VARIANCE)
     PRINT 9012,    FNUMB,CENTROID,STANDDEV,SKEWNESS,KURTOSIS
     MIN = IST
     MAX=IND
     IBELOW = (154 - MIN)/4
     IABOVE = (MAX - 148)/4
     IBELOW = IBELOW - 4*MOD(IBELOW,2)
     IABOVE = IABOVE + 4*MOD(IABOVE,2)
     IHBAR = HBAR + 1.
     IF(IBELOW .GT. IHBAR)    5100,5200
5100 IBELOW = IHBAR
5200 IF(IABOVE .GT. IHBAR)    5300,5400
5300 IABOVE = IHBAR
5400 MIN = 151 - 4*IBELOW
     MAX = 151 + 4*IABOVE
6150 FSPECMAX = FDMAX = 0.
     DO 6200    I = 1,I4
     IF(ASO2NU(I)    .GT. FSPECMAX)    6175,6200
6175 FSPECMAX = ASO2NU(I)
6200 CONTINUE
     DO 6300    I = MIN,MAX
     IF(DENC(I)    .GT. FDMAX)    6250,6300
6250 FDMAX = DENC(I)
6300 CONTINUE
     CALL PLTSPEC (ASO2NU,FNUHT,LPHI,NS,1,FSPECMAX,HBAR)
     CALL PLOTDF (FDMAX,IBELOW,IABOVE,MIN,MAX)
     IF(VEL .LT. 1.0)    6400,6500
6400 NF = NS/4 + 1
     CALL PLTSPEC (ASO2NU,FNUHT,LPHI,NF,1,FSPECMAX,HBAR)
6500 IF(PAUS .NE. 0  .OR.  IFILENUM .EQ. LASTFILE)    6900,6550
6550 LPHI(7) = LPHI(7) + 1
     IF(MOD(IFILENUM,10) .EQ. 0)    6600,100
6600 LPHI(7) = LPHI(7) - 10
     LPHI(7) = LPHI(7) + 64
     IF(IFILENUM .EQ. 9)    6700,100
6700 LPHI(7) = LPHI(7) - 1024
     GO TO 100
6900 PAUSE
     GO TO 100
9099 CALL STOPPLOT
     END
```

```
      SUBROUTINE PLOT2 (MIN,NOS,YMIN,YMAX,ZMIN,ZMAX,LABEL)
      COMMON/SF/SIZE,PLTSPACE,DELT,TIMEMARK
      DIMENSION   Y(4106),Z(4106),X(1026)
      EQUIVALENCE (X,Z(3081))
      COMMON/A/Y,Z
      IF(MIN .EQ. NOS)   60,1
    1 IF(LABEL .GE. 1)   4,2
    2 XC = 0.
      CALL SYMBOL (-1.0,0.04,0.28,17HWAVE HEIGHT (FT.),90.0,17)
      CALL SYMBOL (-1.0,6.04,0.28,17HWAVE HEIGHT (FT.),90.0,17)
    4 XMID = 8.0
      IF(LABEL .GE. 1)   15,6
    6 IMARK = TIMEMARK*DELT/PLTSPACE
      XM = IMARK/2.
      SCALAR1 = INTF(MAX1F(YMAX,ABSF(YMIN)) + 0.9)
      SCALAR2 = INTF(MAX1F(ZMAX,ABSF(ZMIN)) + 0.9)
      CALL PLOT (-0.1,6.0,3)
      CALL PLOT ( 0.0,6.0,2)
      DO 10     I = 7,10
      YY = I
      CALL PLOT ( 0.0,YY,1)
      CALL PLOT (-0.1,YY,1)
      CALL PLOT ( 0.0,YY,1)
   10 CONTINUE
      CALL NUMBER (-0.5, 9.95, 0.105, SCALAR1,0.0,4HF4.0)
      SCALAR1= -SCALAR1
      CALL SYMBOL (-0.5, 7.95, 0.105, 4H 0.0,0.0,4)
      CALL NUMBER (-0.5, 5.95, 0.105, SCALAR1,0.0,4HF4.0)
      SCALAR1= -SCALAR1/2.
   15 XX = XC
      YAMP = Y(MIN)/SCALAR1+ XMID
      CALL PLOT ( XX,YAMP,3)
      YAMP = Y(MIN+1)/SCALAR1+ XMID
      XX = XX + DELT
      CALL PLOT ( XX,YAMP,2)
      MN = MIN + 2
      DO 20    I = MN,NOS
      XX = XX + DELT
      YAMP = Y(I)/SCALAR1 + XMID
      CALL PLOT (XX,YAMP,1)
   20 CONTINUE
      IF(ZMIN .EQ. ZMAX)    55,30
   30 XMID =  2.0
      IF(LABEL .GE. 1)    45,35
   35 CALL PLOT (-0.1,0.0,3)
      CALL PLOT ( 0.0,0.0,2)
      DO 40     I = 1,4
      YY = I
      CALL PLOT ( 0.0,YY,1)
      CALL PLOT (-0.1,YY,1)
      CALL PLOT ( 0.0,YY,1)
   40 CONTINUE
      SCALAR2= 2.*SCALAR2
      CALL NUMBER (-0.5, 3.95, 0.105, SCALAR2,0.0,4HF4.0)
      SCALAR2= -SCALAR2
      CALL SYMBOL (-0.5, 1.95, 0.105, 4H 0.0,0.0,4)
      CALL NUMBER (-0.5,-0.05, 0.105, SCALAR2,0.0,4HF4.0)
      SCALAR2= -SCALAR2/2.
   45 XX = XC + SIZE*DELT
      YAMP = X(MIN)/SCALAR2+ XMID
      CALL PLOT (XX,YAMP,3)
      XX = XX + DELT
```

```
      YAMP = X(MIN+1)/SCALAR2+ XMID
      CALL PLOT (XY,YAMP,2)
      DO 50    I = MN,NOS
      XY = XY + DELT
      YAMP = X(I)/SCALAR2+ XMID
      CALL PLOT (XY,YAMP,1)
   50 CONTINUE
   55 XC = XX
      CALL SPACE00
      RETURN
   60 XX = XC
      IA=XX
      YMID = IA/2
      CALL PLOT (XX, 5.0,3)
      XA = (IA/IMARK)*IMARK
      DO 70    I = 1,IA,IMARK
      CALL PLOT (XA, 5.0,2)
      CALL PLOT (XA, 4.95,1)
      CALL PLOT (XA, 5.05,1)
      CALL PLOT (XA, 5.0,1)
   70 XA = XA - IMARK
      CALL PLOT (0.0,0.0,-3)
      RETURN
      END
```

```
      SUBROUTINE    PLTSPEC (YP,XP,LPH1,NOP,NP,YMAX,HBAR)
      COMMON/SE/SIZE,DELT,PLOTSPEC,TIMEMARK
      DIMENSION    YP(2049)   ,XP(2049),LPH1(10)
C
C     LPH1 CONTAINS PLOTTING LABEL TO BE PLOTTED ON TOP OF PLOT
C     MAXIMUM OF 72 CHARACTERS PLOTTED OUT
C
C     YP(I) - ARRAY OF THE Y VALUES TO BE PLOTTED
C     XP(I) - ARRAY OF THE X VALUES TO BE PLOTTED
C     NOP    - TOTAL NUMBER OF POINTS
C     NP     - STARTING POINT IN ARRAY FROM WHICH TO START PLOTTING
C
      FMAX = IMAX = 16
      XMIN = FMAX/XP(NOP)
    8 SCALE = (INTF(100.*YMAX + 0.99))/100.
      CALL PLOT ( 0.0, -0.1,3)
      CALL PLOT ( 0.0,  1.0,2)
      DO 10    I = 1,9
      Y = I
      CALL PLOT (-0.1, Y,1)
      CALL PLOT ( 0.0, Y,1)
      CALL PLOT ( 0.0,Y+1.,1)
   10 CONTINUE
      SWH = 0.3048*HBAR
      CALL SYMBOL (0.1,10.2,0.175,LPH1,0.0,72)
      CALL SYMBOL (9.0,10.2,0.175,14HSWH =          M,0.0,14)
      CALL NUMBER (9.9,10.2,0.175,SWH,0.0,4HF5.2)
      YY = 9.95
      FLABEL = SCALE
      DECR = SCALE/5.
      DO 20    I = 1,6
      CALL NUMBER (-0.7,YY,0.105,FLABEL,0.0,4HF6.2)
      FLABEL = FLABEL - DECR
      YY = YY - 2.0
      IF(I .EQ. 4)    15,20
   15 CALL SYMBOL (-0.8,4.275,0.175,10HFEET**2/HZ,90.0,10)
   20 CONTINUE
      FMID = FMAX/2.
      L = -1
      DO 38    I = NP,NOP
      YVAL     = (YP(I)   /SCALE)*10.
      XVAL  =     XP(I)*XMIN
      CALL SYMBOL (XVAL,YVAL,       0.07,0,0.0,L)
   38 L = L - 1
      X = FMAX
      CALL PLOT (X,-0.1,3)
      CALL PLOT (X, 0.0,2)
      DO 40    I = 1,IMAX,2
      X = IMAX - I - 1
      CALL PLOT (X, 0.0,1)
      CALL PLOT (X,-0.1,1)
      CALL PLOT (X, 0.0,1)
   40 CONTINUE
      CALL PLOT (-0.1,0.0,1)
      X = -0.3
      IMAX = IMAX + 1
      DO 50    I = 1,IMAX,2
      XX = I - 1
      FREQ = XX/XMIN
      CALL NUMBER (X,-[illegible],0.105,FREQ,0.0,4HF6.[illegible])
      IF(XX .GT. FMID-1.0  .AND.  XX .LT. FMID) [illegible]
   45 CALL SYMBOL (FMID-1.2[illegible]
```

```
50 X = X + 2.0
   CALL PLOT (FMAX+3.0,0.0,-3)
   RETURN
   END
```

```
      SUBROUTINE    PLOTDF(DM,IBELOW,IABOVE,MIN,MAX)
      COMMON/3/DF
      COMMON/4/CENTROID,STANDDEV,SKEWNESS,KURTOSIS
      TYPE REAL    KURTOSIS
      DIMENSION    DF(301)
      DFMAX =(XFIXF(DM + 99.)/100)*100
      NPOINTS = (IABOVE + IBELOW)*4
      INCHES = (NPOINTS + 4)/8
      HALF = INCHES/2. - 0.275
      CALL PLOT (0.0,-0.1,3)
      CALL PLOT (0.0, 1.0,2)
      YY = 1.0
      DO 10   I = 1,9
      CALL PLOT (-0.1,YY,1)
      CALL PLOT ( 0.0,YY,1)
      YY = YY + 1.0
   10 CALL PLOT ( 0.0,YY,1)
      CALL SYMBOL (0.2,10.20,0.175,25HDIST. FN. OF WAVE HEIGHTS,0.0,25)
      CALL SYMBOL (0.2,9.75,0.175,11HCENTROID = ,0.0,11)
      CALL NUMBER (1.85,9.75,0.175,CENTROID,0.0,4HF8.4)
      CALL SYMBOL (0.2,9.50,0.175,11HSTAN DEV = ,0.0,11)
      CALL NUMBER (1.85,9.50,0.175,STANDDEV,0.0,4HF8.4)
      CALL SYMBOL (0.2,9.25,0.175,11HSKEWNESS = ,0.0,11)
      CALL NUMBER (1.85,9.25,0.175,SKEWNESS,0.0,4HF8.4)
      CALL SYMBOL (0.2,9.00,0.175,11HKURTOSIS = ,0.0,11)
      CALL NUMBER (1.85,9.00,0.175,KURTOSIS,0.0,4HF8.4)
      XX =  -0.55
      YY = 9.93
      IDF = DFMAX
      IDFDECR = IDF/5
      DO 20   I = 1,6
      CALL NUMBER (XX,YY,0.14,IDF,0.0,2HI4)
      IF(I .EQ. 3)   14,16
   14                CALL SYMBOL (-0.7,4.575,0.175,6HNUMBER,90.0,6)
   16 YY = YY - 2.0
      IDF = IDF - IDFDECR
   20 CONTINUE
      CALL PLOT (-0.1,0.0,3)
      CALL PLOT ( 0.0,0.0,2)
      XX = 1.0
      DO 30    I = 1,INCHES
      CALL PLOT (XX, 0.0,1)
      CALL PLOT (XX,-0.1,1)
      CALL PLOT (XX, 0.0,1)
   30 XX = XX + 1.0
      IX = IABOVE
      XX = INCHES - 0.16
      INCHES = INCHES + 1
      DO 40    I = 1,INCHES,2
      CALL NUMBER (XX,-0.25,0.14,IX,0.0,2HI3)
      IF(XX 1.0 .LE. HALF  .AND.  XX+1.0 .GT. HALF)  34,38
   34    CALL SYMBOL (HALF,-0.5,0.175,4HFEET,0.0,4)
   38 IX = IX - 4
   40 XX = XX - 2.0
      XX = 0.
      L = -1
      DO 50    I = MIN,MAX
      YY = (DF(I)  /DFMAX)*10.
      CALL SYMBOL (XX,YY,0.08,0.0,0.0,L)
      L = L - 1
   50 XX = XX + 0.125
   60 CONTINUE
```

```
XINCHES = INCHES + 4
CALL PLOT (XINCHES,0.0,-3)
RETURN
END
```

```
      SUBROUTINE FOURIER (A,S,M,IFS)
C
C     THIS ROUTINE PERFORMS AN ANALYSIS OF 2**M POINTS BY FIRST DOING
C     AN ANALYSIS OF 2**M/2 COMPLEX POINTS AND THEN ARRANGING THE RESULTS
C
C     A R G U M E N T S
C     1. A - REAL DATA ARRAY - OF DIMENSION 2**M + 2
C     2. S   SIN/COS TABLE - DIMENSION 2**(M-3)
C     3. M - EXPONENT OF 2 - SIZE OF REAL ARRAY
C     4. IFS - -1 FOR FIRST TIME, -2 THERAFTER
C
      DIMENSION A(1),S(1)
      N = 2**(M-1)
      CALL HARMON(A,S,M-1,IFS,IFERR)
C     MERGE 2 N-POINT ANALYSIS INTO 1 2N-POINT ANALYSIS
      NHALF = N/2
      NTWO = N*2 + 4
      X = XO = COS(3.141592653 6/FLOAT(N))
      Y = YO = SIN(3.1415926536/FLOAT(N))
      DO 1000 K2 = 4,N,2
      K1 = K2 - 1
      N2 = NTWO - K2
      N1 = N2 - 1
      BK1 = A(K1) + A(N1)
      BK2 = A(K2) - A(N2)
      BN1 = A(K2) + A(N2)
      BN2 = A(K1) - A(N1)
      XBN1 = X*BN1
      XBN2 = X*BN2
      YBN1 = Y*BN1
      YBN2=Y*BN2
      A(K1) = .5 *(BK1 + XBN1 - YBN2)
      A(K2) = .5 *(-BK2 + XBN2 + YBN1)
      A(N1) = .5 *(BK1 - XBN1 + YBN2)
      A(N2) = .5 *(BK2 + XBN2 + YBN1)
      Q = X*XO - Y*YO
      Y = Y*XO + X*YO
 1000 X = Q
C     COMPLEX ELEMENT A(N)
      A(2*N+1) =(A(1) - A(2))*.5
      A(2*N+2) = 0.0
C     COMPLEX ELEMENT A(0)
      A(1) = .5*(A(1)+A(2))
      A(2) = 0.0
C     COMPLEX ELEMENT A(N/2)
C     A(N+1) = A(N+1)
C     A(N+2) = A(N+2)
      RETURN
      END
```

```
      SUBROUTINE HARMON(A,S,M,IFS,IFERR)
      DIMENSION A(1),S(1)
C        HARM, ONE-DIMENSIONAL BASIC FORTRAN VERSION,  J.W.COOLEY         HARM 001
C     MODIFIED TO RUN ON CDC 3800 AND TO ANALYIZE UP TO 2**14 NUMBERS.
C                                                                         HARM 002
C                                                                         HARM 008
C     DOES EITHER FOURIER SYNTHESIS,I.E.,COMPUTES COMPLEX FOURIER SERIESHARM 009
C     GIVEN A VECTOR OF N COMPLEX FOURIER AMPLITUDES,OR, GIVEN A VECTOR HARM 010
C     OF COMPLEX DATA X DOES FOURIER ANALYSIS, COMPUTING AMPLITUDES.    HARM 011
C     A IS A COMPLEX VECTOR OF LENGTH N=2**M COMPLEX NOS. OR 2*N REAL   HARM 012
C     NUMBERS. A IS TO BE SET BY USER.                                  HARM 013
C     M IS AN INTEGER SUCH THAT 0.LT.M.LE.14  SET BY USER.
C     S IS A VECTOR S(J)= SIN(2*PI*J/NP ), J=1,2,.,...,NP/4-1,          HARM 015
C     COMPUTED BY PROGRAM.                                              HARM 016
C     IFS IS A PARAMETER TO BE SET BY USER AS FOLLOWS-                  HARM 017
C     IFS=0 TO SET NP=2**M AND SET UP SINE TABLE S.                     HARM 018
C     IFS=1 TO SET N=NP=2**M, SET UP SIN TABLE, AND DO FOURIER          HARM 019
C     SYNTHESIS, REPLACING THE VECTOR A BY                              HARM 020
C                                                                       HARM 021
C     X(J)= SUM OVER K=0,N-1 OF A(K)*EXP(2*PI*I/N)**(J*K),              HARM 022
C     J=0,N-1, WHERE I=SQRT(-1)                                         HARM 023
C     THE  X'S  ARE STORED WITH   RE X(J) IN CELL  2*J+1                HARM 024
C     AND  IM X(J)  IN CELL  2*J+2  FOR  J=0,1,2,.,..,N-1.              HARM 025
C     THE  A'S  ARE STORED IN THE SAME MANNER.                          HARM 026
C                                                                       HARM 027
C     IFS=-1   TO SET  N=NP=2**M,SET UP SIN TABLE, AND DO FOURIER       HARM 028
C     ANALYSIS, TAKING THE INPUT VECTOR A AS X AND                      HARM 029
C     REPLACING IT BY THE A  SATISFYING THE ABOVE FOURIER SERIES.       HARM 030
C     IFS=+2 TO DO FOURIER SYNTHESIS ONLY, WITH A PRE-COMPUTED S.       HARM 031
C     IFS=-2 TO DO FOURIER ANALYSIS ONLY, WITH A PRE-COMPUTED S.        HARM 032
C     IFERR   IS SET BY PROGRAM TO-                                     HARM 033
C     =0 IF NO ERROR DETECTED.                                          HARM 034
C     =1 IF M IS OUT OF RANGE,, OR, WHEN IFS=+2,-2, THE                 HARM 035
C     PRE-COMPUTED S TABLE IS NOT LARGE ENOUGH.                         HARM 036
C     =-1 WHEN IFS =+1,-1, MEANS ONE IS RECOMPUTING S TABLE             HARM 037
C     UNNECESSARILY.                                                    HARM 038
C                                                                       HARM 039
C     NOTE- AS STATED ABOVE, THE MAXIMUM VALUE OF M FOR THIS PROGRAM    HARM 040
C     ON THE IBM 7094 IS 13. ON 360 MACHINES HAVING GREATER STORAGE     HARM 041
C     CAPACITY, ONE SHOULD CHANGE THIS LIMIT BY REPLACING 13 IN         HARM 042
C     STATEMENT 3 BELOW BY LOG2 N, WHERE N IS THE MAX. NO. OF           HARM 043
C     COMPLEX NUMBERS ONE CAN STORE IN HIGH-SPEED CORE.                 HARM 044
C           IF THE CAPACITY OF  HARM  IS TO BE INCREASED, ONE MUST      HARM 045
C     ALSO ADD MORE  DO  STATEMENTS TO THE BINARY SORT ROUTINE          HARM 046
C     FOLLOWING STATEMENT  24  AND CHANGE THE EQUIVALENCE STATEMENTS    HARM 047
C     FOR THE  K'S.                                                     HARM 048
C                                                                       HARM 049
      DIMENSION  K(15)
      EQUIVALENCE (K(14),K1),(K(13),K2),(K(12),K3),(K(11),K4)
      EQUIVALENCE (K(10),K5),(K( 9),K6),(K( 8),K7),(K( 7),K8)
      EQUIVALENCE (K( 6),K9),(K( 5),K10),(K(4),K11),(K(3),K12)
      EQUIVALENCE (K(2),K13),(K( 1),K14),(K(1),N2)
      IF(M)2,2,3                                                        HARM 055
    3 IF(M .LE. 14)    5,2
    2 IFERR=1                                                           HARM 057
    1 RETURN                                                            HARM 058
    5 IFERR=0                                                           HARM 059
      N=2**M                                                            HARM 060
      IF( IABS(IFS) - 1 ) 200,200,10                                    HARM 061
C     WE ARE DOING TRANSFORMS ONLY, SEE IF PRE-COMPUTED                 HARM 062
C     S TABLE IS SUFFICIENTLY LARGE                                     HARM 063
   10 IF( N-NP )20,20,12                                                HARM 064
```

```
   12 IFERR=1                                                           HARM 065
      GO TO 200                                                         HARM 066
C     SCRAMBLE A, BY SANDE'S METHOD                                     HARM 067
   20 K(1)=2*N                                                          HARM 068
      DO 22 L=2,M                                                       HARM 069
   22 K(L)=K(L-1)/2                                                     HARM 070
      DO 24  L=M,13
   24 K(L+1)=2                                                          HARM 072
C     NOTE EQUIVALENCE OF KL AND K(14-L)                                HARM 073
C     BINARY SORT-                                                      HARM 074
      IJ=2                                                              HARM 075
      JI=2
   25 DO 30 J2=J1,K2,K1
      DO 30 J3=J2,K3,K2                                                 HARM 078
      DO 30 J4=J3,K4,K3                                                 HARM 079
      DO 30 J5=J4,K5,K4                                                 HARM 080
      DO 30 J6=J5,K6,K5                                                 HARM 081
      DO 30 J7=J6,K7,K6                                                 HARM 082
      DO 30 J8=J7,K8,K7                                                 HARM 083
      DO 30 J9=J8,K9,K8                                                 HARM 084
      DO 30 J10=J9,K10,K9                                               HARM 085
      DO 30  J11 = J10,K11,K10
      DO 30  J12 = J11,K12,K11
      DO 30  J13 = J12,K13,K12
      DO 30  JI  = J13,K14,K13
      IF(IJ-JI)28,30,30                                                 HARM 089
   28 T=A(IJ-1 )                                                        HARM 090
      A(IJ-1)=A(JI-1)                                                   HARM 091
      A(JI-1)=T                                                         HARM 092
      T=A(IJ)                                                           HARM 093
      A(IJ)=A(JI)                                                       HARM 094
      A(JI)=T                                                           HARM 095
   30 IJ=IJ+2                                                           HARM 096
      JI=JI+2
      IF(K1-JI)31,25,25
   31 IF(IFS)32,2,36                                                    HARM 097
C     DOING FOURIER ANALYSIS,SO DIV. BY N AND CONJUGATE.                HARM 098
   32 FN = FLOAT(N)
      DO 34 I=1,N                                                       HARM 100
      A(2*I-1) = A(2*I-1)/FN                                            HARM 101
   34 A(2*I)=-A(2*I)/FN                                                 HARM 102
C     SPECIAL CASE- L=1                                                 HARM 103
   36 DO 40 I=1,N,2                                                     HARM 104
      T = A(2*I-1)                                                      HARM 105
      A(2*I-1) =T + A(2*I+1)                                            HARM 106
      A(2*I+1)=T-A(2*I+1)                                               HARM 107
      T=A(2*I)                                                          HARM 108
      A(2*I) = T + A(2*I+2)                                             HARM 109
   40 A(2*I+2)= T - A(2*I+2)                                            HARM 110
      IF(M-1) 2,1   ,50                                                 HARM 111
C     SET FOR L=2                                                       HARM 112
   50 LEXP1=2                                                           HARM 113
C     LEXP1=2**(L-1)                                                    HARM 114
      LEXP=8                                                            HARM 115
C     LEXP=2**(L+1)                                                     HARM 116
      NPL= 2**MT                                                        HARM 117
C     NPL = NP* 2**-L                                                   HARM 118
      DO 130 L=2,M
C     SPECIAL CASE- J=0                                                 HARM 120
      DO 80 I=2,NP,LEXP                                                 HARM 121
      I1=I + LEXP1                                                      HARM 122
      I2=I1+ LEXP1                                                      HARM 123
      I3 =I2+LEXP1                                                      HARM 124
      T=A(I-1)                                                          HARM 125
      A(I-1) = T +A(I2-1)                                               HARM 126
      A(I2-1) = T-A(I2-1)                                               HARM 127
```

```
      T =A(I)
      A(I) = T+A(I2)
      A(I2) = T-A(I2)
      T= -A(I3)
      TI = A(I3-1)
      A(I3-1) = A(I1-1) - T
      A(I3   ) = A(I1 )   - TI
      A(I1-1) = A(I1-1) +T
   80 A(I1)    = A(I1   )   +TI
      IF(L-2) 120,120,90
   90 KLAST=N2-LEXP
      JJ=NPL
      DO 110 J=4,LEXP1,2
      NPJJ=NT-JJ
      UR=S(NPJJ)
      UI=S(JJ)
      ILAST=J+KLAST
      DO 100 I= J,ILAST,LEXP
      I1=I+LEXP1
      I2=I1+LEXP1
      I3=I2+LEXP1
      T=A(I2-1)*UR-A(I2)*UI
      TI=A(I2-1)*UI+A(I2)*UR
      A(I2-1)=A(I-1)-T
      A(I2  )=A(I   ) - TI
      A(I-1)  =A(I-1)+T
      A(I)    =A(I)+TI
      T=-A(I3-1)*UI-A(I3)*UR
      TI=A(I3-1)*UR-A(I3)*UI
      A(I3-1)=A(I1-1)-T
      A(I3)    =A(I1   )-TI
      A(I1-1)=A(I1-1)+T
  100 A(I1)    =A(I1)    +TI
C     END OF I LOOP
  110 JJ=JJ+NPL
C     END OF J LOOP
  120 LEXP1=2*LEXP1
      LEXP = 2*LEXP
  130 NPL=NPL/2
C     END OF L LOOP
      IF(IFS)145,2,1
CC    DOING FOURIER ANALYSIS. REPLACE A BY CONJUGATE.
  145 DO 150 I=1,N
  150 A(2*I) =-A(2*I)
      GO TO 1
C     RETURN
C     MAKE TABLE OF S(J)=SIN(2*PI*J/NP),J=1,2,...,NT-1,NT=NP/4
  200 NP=N
      MP=M
      NT=N/4
      MT=M-2
      IF(MT) 260,260,205
  205 THETA=.7853981634
C     THETA=PI/2**(L+1)      FOR L=1
      JSTEP = NT
C     JSTEP = 2**( MT-L+1 ) FOR L=1
      JDIF = NT/2
C     JDIF = 2**(MT-L)  FOR L=1
      S(JDIF) = SIN(THETA)
      IF (MT-2)260,220,220
  220 DO 260 L=2,MT
      THETA = THETA/2.
      JSTEP2 = JSTEP
      JSTEP = JDIF
      JDIF = JDIF/2
      S(JDIF)=SIN(THETA)
```

```
      JC1=NT-JDIF
      S(JC1)=COS(THETA)
      JLAST=NT-JSTEP2
      IF(JLAST-JSTEP)250,230,230
  230 DO 240 J=JSTEP,JLAST,JSTEP
      JC=NT-J
      JD=J+JDIF
  240 S(JD)=S(J)*S(JC1)+S(JDIF)*S(JC)
  250 CONTINUE
  260 IF(IFS)20,1,20
      END
```

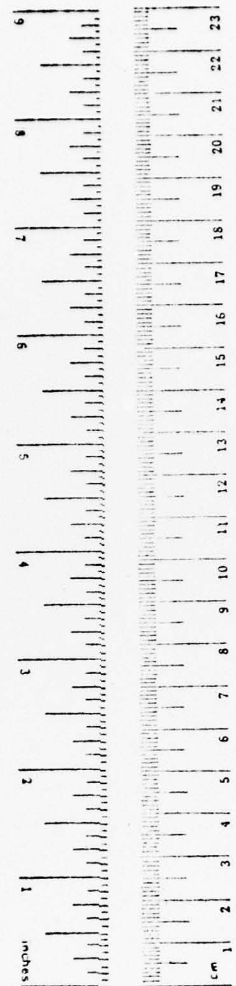
```
      SUBROUTINE UNPKSHIP(INCH8,I)
      COMMON/A/RADRNG(4106),ROLL(4106)
      COMMON/B/NBUFF(513)
      DIMENSION INCH8(12),NBUFF1(3),N1(2)
      TYPE INTEGER RADRNG,ROLL
      DATA (M1=3777B),(M2=2000B),(M3=7777777777774000B)
      I1=0
      DO 9 K1=1,513,3
      I1=I1+1
      I2=(I-1)*171+I1
      DO 4 J=1,3
      NBUFF1(J)=NBUFF(K1+J-1)
    4 CONTINUE
      I3=0
      DO 8 K=1,12
      IF(INCH8(K).NE.0)1,8
    1 I3=I3+1
      IWORD=(INCH8(K)-1)/4+1
      INDEX=12*(IWORD*4-INCH8(K))+1
      NTS=NBUFF1(IWORD)/2**INDEX
      NTS=NTS.AND.M1
      NSIGN=NTS.AND.M2
      IF(NSIGN.NE.0)6,7
    6 NTS=NTS-1
      NTS=NTS.OR.M3
    7 CONTINUE
      N1(I3)=NTS
    8 CONTINUE
      RADRNG(I2)=N1(1)
      ROLL(I2)=N1(2)
    9 CONTINUE
      RETURN
      END
```

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

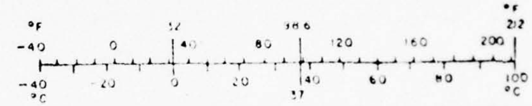
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SL - 7 -13		

4. Title and Subtitle	5. Report Date
A REPORT ON SHIPBOARD WAVEHEIGHT RADAR SYSTEM	April, 1978
	6. Performing Organization Code
	8. Performing Organization Report No.
7. Author(s): D. Chen and D. Hammond	
9. Performing Organization Name and Address: U.S. Naval Research Laboratory, Washington, D.C. 20375	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.: MIPR Z-70099-4-43693
	13. Type of Report and Period Covered: Final Report
12. Sponsoring Agency Name and Address: Commandant (G-DST), U.S. Coast Guard Headquarters, Office of Research & Development, Washington, D.C. 20590	14. Sponsoring Agency Code: G-DST-2

15. Supplementary Notes

16. Abstract

ABSTRACT

A microwave shipboard wave-height radar sensor for measuring ocean wave spectra, developed by the Naval Research Laboratory, was installed on the containership *S.S. McLEAN*, February, 1975. The sensor's performance, design, and analysis of data for one data run are discussed. The radar system has a 3 centimeters wavelength, 2 nanoseconds pulse width, 100 watts of peak transmitted power, 10,000 pulse per second repetition rate, 2-foot parabola antenna diameter, 7 decibel receiver noise figure, 100 pulses per second equivalent pulse processing rate, and a 1-foot resolution. Results are in reasonable agreement with airborne measurements. Areas for improving the system are also discussed.

17. Key Words	18. Distribution Statement
	Document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	73	

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